THE ECOLOGICAL SUSTAINABILITY OF POTATO PRODUCTION IN THE SANDVELD REGION OF THE WESTERN CAPE: NUTRIENT AND WATER USE EFFICIENCIES

by

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DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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If the research does not cause some form of stir in society, reassess its need.

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PREFACE

This thesis is presented as a compilation of six chapters. Each chapter is introduced separately and is written according to the style of the South African Journal of Plant and Soil.

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III. LIST OF ABREVIATIONS

AE	Application Efficiency
AET	Actual Evapotranspiration
AI	Actual Irrigation
ARC	Agricultural Research Council
AUE	Agronomic Use Efficiency
Ca	Calcium
CU	Coefficient of Uniformity
CU_{HH}	Coefficient of Uniformity (Heermann and Hein)
DAE	Days after Emergence
DAP	Days after Planting
DCT	Divergence Control Tube
DM	Dry Matter
DU	Distribution Uniformity
DU_{lq}	Distribution Uniformity of the lowest quarter (25%)
E	Evaporation
EC	Electrical Conductivity
ET	Evapotranspiration
ET_o	Potential Evapotranspiration
FI	Fractional Interception
GWR	Gross Water Requirement
IR	Irrigation Requirement
IWP	Irrigation Water Productivity
IWUE	Irrigation Water Use Efficiency
K	Potassium
K_c	Crop Coefficient
Kcb	Basal Crop Coefficient Curve

LAI	Leaf Area Index
LR	Leaching requirement
Mg	Magnesium
N	Nitrogen
Na	Sodium
NUE	Nutrient Use Efficiency
NU_pE	Nutrient Uptake efficiency
NU_tE	Nutrient Utilisation efficiency
P	Phosphorus
PAR	Photosynthetically Active Radiation
RUE	Resource Use Efficiency
S	Sulphur
SG	Specific Gravity
SWB	Soil Water Balance
SWC	Soil Water Content
SWCC	Soil Water Characteristic Curve
SWRC	Soil Water Retention Curve
TWR	Total Water Requirement
WUE	Water Use Efficiency

IV. ABSTRACT

Uncertainty regarding the rate at which water and nutrients move and are distributed throughout the soil profile is key in managing potato production systems in the Sandveld region of the Western Cape. The sandy soils with low nutrient and water holding capacities complicate irrigation water management and fertiliser practices. Information on efficient water management practices is scarce due to the difficulties of measuring water losses to the environment. Thus, the aim of this study was to quantify inputs and losses in potato production systems in the Sandveld region to close the gap in knowledge with regards to water and nutrient leaching under current management practices. The study was conducted on nine potato fields (processing cultivar FL2108 and table cultivar Sifra) between March 2018 and March 2019 under centre-pivot irrigation systems. Water inputs were monitored with flow meters and pressure transducers. Nutrient and water losses (drainage and leaching) was assessed using drainage lysimeters and soil water movement throughout the profile was monitored with the use of capacitance probes. Tuber yield was determined when the crop was mature, and soil-water balance components as well as water and nutrient-use efficiencies were calculated. The regular evaluation of irrigation systems is recommended to prevent over or under application of water to combat inefficiencies and meet the evapotranspiration demands of the crop. The simulation of evapotranspiration through adjusted basal crop coefficient curves to meet the demands of the specific areas was indicated to be a good measure of crop water use. Evapotranspiration values obtained ranged from 188 to 647 mm. Irrigation is generally not adjusted to crop physiological needs, resulting in over application of water, particularly during winter due to the effect that rainfall has on the increased potential of drainage. The rainfall recorded ranged from 54 to 271 mm. Substantial drainage occurred in summer planted crops as a result of irrigation water exceeding crop requirements. However, as a result of the rapid depletion of water in the soil profiles due to low water holding capacities, farmers cannot leave substantial room in the profile for rainfall. Weather station data and soil capacitance probes provided good information regarding the potential occurrence of drainage events and are recommended as management tools. Large nutrient losses were associated with substantial drainage, occurring on average at 70 kg N ha^{-1}, 52 kg P ha^{-1} and 138 kg K ha^{-1}. Drainage collected ranged from 4 to 302 mm per season. Water use efficiency observed was average (65.4 to 122.2 kg mm^{-1}), which is accredited to low yields and high drainage losses in winter. Yields ranged from 34.7 to 118.2 t ha^{-1}. Relatively low yields in winter and autumn resulted from cool temperatures and less available solar radiation in these periods. Yields during winter where below 60 t ha^{-1}, compared to summer crops, which yielded 59.0 and 118.2 t ha^{-1}.

Key words: water-use efficiency, nutrient use efficiency, nutrient leaching, drainage lysimeter, soil water balance, evapotranspiration.

CHAPTER 1: INTRODUCTION

1.1 Study background

The rising human population paired with current political agendas to push economic growth, has led to increased pressure on the earth's natural resources and ecosystems (Reid et al. 2005). An estimated global population increase from 7 to 9.7 billion people by 2050 will place a burden on agricultural production to ensure worldwide food security (FAOSTAT 2016). Tilman et al. (2011) forecasted an increase in global crop demand (human foods, livestock and fish feeds) of 100 to 110% from 2005 to 2050. Therefore, the growth and improved efficiency of the agricultural sector is an important component in reducing global hunger and malnutrition. However, paired with this demand on agriculture to rapidly develop and perform is a concern regarding sustainability within crop production systems, with emphasis being on the effects that certain farming management practices have on local ecological habitats (Kashyap and Panda 2001; Mueller et al. 2012).

In the 1960s, the world saw a threat to humanity through one of its largest known issues, *famine*, which was leading up to affect the globe and seen to be inevitable in developing countries (Pingali 2012). These events gave rise to the start of the '*Green Revolution*' in the 1960s and 1970s, resulting in the use of hybrid plants, chemical fertilisers, pesticides and fungicides. This aided developing countries by increasing crop yields to supply the increasing population's demand with a staple food diet and vanquish hunger, ultimately achieving this without having to convert more land to agricultural cultivation (Pingali 2012). The high yields came with detrimental consequences as farms turned into monocultures and mechanised operations. After a few years, pests and weed resistance increased as well as loss of soil organic carbon due to heavy tillage and an increased use of fertilisers, causing the combined pollution and contamination of groundwater as well as rivers (Stewart et al. 2006; Erisman et al. 2007; Meier et al. 2015; Capellesso et al. 2016). Inevitably, the effects of the '*Green Revolution'*, once portrayed as the world's saving grace, aided the rise of global temperatures and CO_2 emissions, leading to overall degradation of the earth and its resources (Van Pham and Smith 2014).

Potato (*Solanum tuberosum*) is a crop that aided in eliminating world hunger due to the tuber's ability to feed significant numbers of people with high calorie input from cultivation of less land (Brown and Henfling 2014; Haverkort et al. 2015). Potato tubers are grown worldwide, being the fourth most important crop following rice, maize and wheat (FAOSTAT 2016). This importance is a factor of the crop's versatile adaptive range, combined with its simplicity of cultivation (Devaux et al. 2014). The tuber's stable nutritional status allows it to be a staple diet in developing countries and due to its scarce status in global trade markets it is not at risk to political agenda, unlike some major cereals, thus, it is a crop that is highly recommended by the World Food and Agriculture Organisation (FAO) as a food security product. Developing countries and majority of the hungry depend on agriculture and its related values to provide nutrition as well as a livelihood. Potato cropping systems thus, provide direct access to either nutritious food or an income through trade with little vulnerability from food price fluctuations (Devaux et al. 2014).

Potatoes are the most important vegetable crop grown in South Africa (Joubert et al. 2010). South Africa is the third largest producer of potatoes within Africa, following Algeria and Egypt (FAOSTAT 2016). The industry has developed into the largest vegetable crop within the country (Van Zyl and Van der Merwe 2016). The production area of potato cultivation in South Africa amounts to approximately 50 to 60 thousand hectares, but fluctuates yearly (Potatoes South Africa 2019). The versatility and relative ease in cultivation contributes to the distribution of production areas within South Africa (Devaux et al. 2014). Within the country, there are 16 distinct geographical regions where potato cultivation occurs. The main regions being northern Limpopo, the Sandveld area of the Western Cape, as well as the east and western regions of the Free State (Steyn et al. 2016). South Africa consists of climates varying from dry winters and rainy summers in the interior to a Mediterranean-type climate in the southwestern coastal areas that are characterised by hot dry summers and cool, rainy winters. Therefore, planting time varies considerably within the country. Most inland regions within South Africa are limited to only producing potatoes during the summer season due to winter frosts. In the Limpopo Province, rainy summers are too hot for tuber production, which is attributed to by low altitudes. Therefore, potatoes are only grown in the winter and early spring (May-Sept) under irrigation within this region. The Free State potato production areas are susceptible to frost due to higher altitudes and a lower latitude than the Limpopo region and hence, potato production can only take place during summers when rain events occur.

The fluctuating market prices in the country however, puts strain on producers and the infrastructure of potato production systems. As a result, there has been a rapid decline in the area of land under potato cultivation from the 1990s to 2019, with a reduction of 13 500 ha (Potatoes South Africa 2019). The decline was not matched by a decrease in productivity within the country as yields were increased. Yield, in terms of million bags of 10 kg, has grown exponentially from the mid-1990s until 2018, with the exception of 2002. The increase in yield was attributed to an increase in irrigation technology, improved cultivars and cultivation techniques (Haverkort et al. 2013; Zyl and Van der Merwe 2016). The shift towards irrigated systems in 1993 due to the instability of market prices and unreliability of rainfall resulted in a more productive and stable industry. With this shift came a surge in inputs and energy resulting in affected resource use efficiencies and over application of nutrients. Producers have the equipment to irrigate, but there is a lack of tools, knowledge and understanding of what stage as well as at what rates to apply water and nutrients.

The term "*sustainability"* is regarded as a multifaceted concept with little agreement regarding its dimensions between academics (Pretty 2008). There have been various works on determining principles to measure agricultural sustainability under differing ecosystems (Lin and Routray 2003; Pretty 2008; Kareemulla et al. 2017). Sustainability however, can generally be regarded as the production of high-quality produce with the efficient use of resource inputs. Safeguarding and improving the conditions of natural resources and ecosystems as well as the social and economic status of the producers, is at the forefront of this concept (SAIP 2019). Ecological sustainability within potato production systems in South Africa has been studied extensively by Steyn et al. (2016) using resource use efficiency parameters such as land, water, chemicals, fertiliser, energy and seed. The 16 regions within South Africa varied significantly in resource use efficiency. Farms within these regions also varied, depending on differing management practices implemented. High resource use efficiency regions were reported to be the Mpumalanga highveld, southern Cape and western Free State. High input areas with low resource use efficiency were the Sandveld and Gauteng regions. Low resource use efficiency within the Gauteng region is historically due to the majority of farmers previously producing vegetable crops. The high nutrient requirement of many vegetable production systems in this area has resulted in farmers transferring high fertiliser application rates into newly formed potato cropping systems. Previous vegetable cultivation may also have resulted in high levels of residual elements left in the rooting zone. The lack of knowledge for correct water and nutrient application on potato crops has led to higher inputs in the area.

The rise in agriculture production of potatoes in the Sandveld has led to increased discussions regarding the region's ecological sustainability (De Wit 2013). The Sandveld area is one of the locations in South Africa with the highest number of potato growers. There are currently 82 commercial producers (Potatoes South Africa 2019). The location's sandy soils and low relief topography as well as a surplus of groundwater availability have contributed to the use of centre-pivot irrigation and the growth of the area's potato industry (Archer et al. 2009). Its total regional contribution to the processing industry within South Africa is 14% (Potatoes South Africa 2019).

Potatoes are grown in both the winter and summer seasons in the region's Mediterranean-type climate (Taljaard 1986). Due to the Sandveld's location being near the Atlantic Ocean, the wind coming off the sea keeps temperatures cool enough in the summer for production and prevents frost in the winter months (Haverkort et al. 2013). However, due to low and sporadic rainfall, and an ever-changing climate, irrigation is required to ensure adequate supply of water to achieve economically feasible yields (Archer et al. 2009). An abundance of good quality ground water and high economic returns has aided the industry's expansion in the area (Archer et al. 2009). The Sandveld's sandy soil texture results in uncertainty with regards to the rate and distribution with which water and nutrients moves through the profile. This leads to ambivalence when it comes to fertiliser and water application rates and timing. Over application is a common occurrence and can cause detrimental ecological and economic impacts due to lower resource use efficiency and increased leaching. Leaching of nutrients occurs easily since the soil has a low clay content and consequently a low cation exchange capacity, resulting in ions not being held by the soil particles and translocation of nutrients down the soil profile taking place (Bleam 2016). The rate of percolation as well as loss of nutrients and water is generally considered quicker in sandy soils (Hillel 2004). A shallow root system, such as that of potato crops, will magnify the problem of leaching as its capacity to absorb large amounts of nutrients is limited (Hillel 2004). Nutrients in sandy soils are considered leached below the root zone of the potato crop, which is in general around 40 to 60 cm deep (Ahmadi et al. 2011; Rykaczewska 2015). However, most water is taken up in the first 10 to 15 cm of the soil profile (Alva 2008; Stalham and Allan 2001) with 90% of the roots being located in the upper 25 cm (Shrestha et al. 2010).

Because the Sandveld region is arid or semi-arid, with rainfall averaging 150 to 300 mm per annum, farmers rely on borehole irrigation to produce potatoes. Sound irrigation management, including irrigation scheduling, is critical for optimising potato production efficiency, whilst minimising its impact on the environment. The future increase in the Sandveld's average temperatures and decrease in rainfall, as forcasted by Archer et al. (2009), will further result in the application of larger quantities of irrigation water and may lead to lower groundwater recharge. The controversial topic of groundwater recharge with climate change is complicated further by a study done in the Sandveld region using system dynamics modelling (De Wit 2013). This study concludes that at no point up to 2030 is depletion of the underground aquifer an issue for farmers within the area. The increase in irrigation and nutrient application will nonetheless lead to losses through leaching and drainage, negatively impacting producers as well as the natural habitat (Mueller et al. 2012; Steyn et al. 2016). The use of water can be improved through the application of optimal irrigation practices and scheduling, which is essentially governed by crop evapotranspiration (ET) (Kashyap and Panda 2001). A crop's evapotranspiration will shift as the growth stages change and therefore, water requirements will follow this trend. This change in ET needs to be accounted for in order to attain high water use efficiency, minimise drainage and reduce ground water contamination (Kashyap and Panda 2001). One of the biggest issues faced in the cultivation of potatoes in the Sandveld region is the uncertainties that farmers face during the application of water and nutrients through irrigation with regards to rates and timing. The primary management strategies for sandy soils should be to apply appropriate rates of water and nutrients at critical periods of crop growth (Shrestha et al. 2010). The use of controlled-release fertilisers coated by sulphur or polymer could be a possible strategy to reduce nitrogen leaching. However, studies on controlled-release fertilisers in potato production systems have shown both positive (Hutchinson et al. 2003) and negative results (Waddell et al. 1999). The primary limitations are economic and ensuring that fertiliser release rates meet the nitrogen requirements of the crop (Zebarth and Rosen 2007). Farmers are often reluctant to use scheduling equipment in their irrigation systems or keep to broad guidelines of nutrient and irrigation management practices. This can be attributed to by high costs of equipment, unavailability or lack of access and the time required in setting up and monitoring these systems. Another limitation to farmers is the paucity of information on nutrient and irrigation management tailored for the Sandveld region. There is a lack of knowledge in nutrient and water requirements in this area, resulting in over application, which in turn leads to nutrient and water waste into the environment, which has a negative ecological impact (Hillel 2004; Tilman et al. 2011).

The Sandveld is dominated by agricultural production with the main ecological constraints being on the conversion of natural vegetation to cultivated land, pressure of groundwater availability and climate change (De Wit 2013). The conversion of *fynbos* vegetation into potato production systems and arable land is of particular concern as it is at present threatening the diversity of *fynbos* in the Sandveld. The topic of conservation is discussed extensively within the region due to the *fynbos* established within its borders. This floral system is classified as the Cape Floral Kingdom and contains over 1 500 species of vascular plants, making this vegetation unique to the area and considered important to preserve (Archer et al. 2009). The high levels of irrigation used threaten the ecosystem by potentially reducing groundwater levels and water quality (Franke et al. 2011). The movement of excess nutrients into the environment such as nitrates and phosphates can cause eutrophication as well as affect human health through contaminated water sources used for drinking (Stewart et al. 2006). The response to environmental degradation is however, advancing towards "*sustainable intensification*" in order to prevent agriculture further affecting ecological systems, and aiding increasing yields on landscapes classified with poor fertility (Matson and Vitousek 2006; Burney et al. 2010; Tilman et al. 2011; Mueller at al. 2012). There is thus a movement to reduce the agricultural impact on the environment through reducing nutrient overuse and crop inputs, such as excessive tillage and over-irrigation wherever possible (Carter and Sanderson 2001).

Research worldwide has been conducted on the effects of reduced tillage on soil properties. The positive impacts of conservation tillage have been illustrated extensively in the Western Cape (Agenbag and Maree 1989; Botha 2013; Wiese 2013). Wiese (2013), conducted a study in the Swartland region of the Western Cape, the research confirmed that tillage influenced both soil water and mineral nitrogen content. This is reported to be attributed to by increased rates of infiltration and reduced soil water evaporation (Page et al. 2013). This is in agreement with Taylor et al. (2012), whom researched conservation agriculture in KwaZulu-Natal. Even for the contrasting climatic regions and varying soil types, both KwaZulu-Natal and the Western Cape researches concluded that under conservation tillage systems plant available water was significantly greater than under conventional tillage. However, even with all the positive reports on conservation tillage, it still has not fully been adopted within the Sandveld region, as it is difficult to implement within potato production systems due to the destructive nature of the harvesting process.

New and improved management practices are therefore, required to prevent the collapse of the ecosystem within this region, at the same time maintaining the potato industry by closing the yield gap. The yield gap refers to the potential yield that can be obtained in an area in comparison to the observable yield (Mueller et al. 2012; Haverkort et al. 2015). The pressure associated with the demand to increase yields is sometimes conflicting with the requirements of long-term ecological sustainability (Harris 1996). Without scientific evidence of the best management practices to ensure sustainable intensification, progress will not be possible. There is substantial room for improvement in production efficiency through management practices (Steyn et al. 2016). Sustainability of irrigation within agricultural systems is reliant on efficient management practices to enhance crop productivity. Information of such management practices are hard to find due to a lack of proof regarding actual losses to the environment. Thus, leaching and drainage need to be quantified, allowing strategies to better manage input resources to be devised.

1.2 Aim and objectives

The aim of this study was to quantify inputs and losses occurring in potato production systems in the Sandveld region of the Western Cape. The study was conducted in order to close the gap in knowledge with regard to water and nutrient leaching under current management practices. The research did not look at altering management strategies to improve production, but investigated current potato cropping inputs and losses and through that, recommendations of how best to improve efficiencies along with further enhancements to the research can be made. The benefit of quantifying losses and system inefficiencies for producers will allow them to optimise production and reduce unnecessary input costs. Apart from agronomic and economic benefits towards farmers of improved nutrient and water use efficiencies, the need to protect the fragile ecosystem present within the Sandveld region is also evident. Nutrient leaching into groundwater and water sources, as well as refining and preventing excessive waste of water, should be limited. By understanding the causes of drainage, crop evapotranspiration changes and climatic conditions throughout the growth cycle, management practices to optimise inputs and resource use efficiency can be recommended as well as future research requirements. To address these needs, the study was approached through four objectives:

1. *To assess the efficiency of irrigation systems with regards to water application in the Sandveld growing region.*
2. *To compare actual water application with simulated crop irrigation requirements and identify crop water needs for specific growing seasons to assess potential over- or under-irrigation.*
3. *To quantify drainage and assess the effect of irrigation water and rainfall on drainage accumulation and water use efficiency as well as to investigate methods of irrigation scheduling to improve efficient water use in the region.*
4. *To compare actual yields with simulated attainable yields and explore management strategies that can be implemented to increase nutrient use efficiency.*

CHAPTER 2: LITERATURE REVIEW

2.1 Resource use efficiency

This literature review aims at exploring the concept of water and nutrient use efficiency to understand the possible environmental implications for potato producers in the Sandveld region and the knowledge required to move towards a more sustainable industry.

Resource use efficiency (RUE) has been used as a tool to measure ecological and financial sustainability in potato production regions. It is a parameter that differs substantially between locations as well as within production areas as farming practices, income, access and availability of resources all vary (Haverkort et al. 2014; Steyn et al. 2016). Measuring RUE can potentially provide information regarding optimising various management techniques to prevent waste, protect the environment and close yield gaps. The wide range of parameters affecting RUE however, brand it a dynamic form of monitoring sustainability of systems. Indicating the effect of various components on RUE is a study by Haverkort et al. (2014) on the ecological footprints of potato production systems in Chile. The research concluded that large farms showed a lower land footprint, due to access to improved technologies compared to small farms with lower incomes. The application of more water and fertiliser by the larger farms however, resulted in higher CO_2 emissions and water use. An increase in the availability of resources can hence, result in lower RUE (Haverkort et al. 2014). The land footprint is not only a management and human-based factor but is further complicated by climatic and locality effects, as shown by Steyn et al. (2016). The areas that were located at mid-altitudes and under irrigation resulted in the highest land use efficiency due to stable temperatures in the summer months. Dryland potato production regions relying on rainfall only, such as KwaZulu-Natal and the northern parts of the Eastern Cape, showed low land-use efficiency due to unreliable rainfall patterns during the growing season. In addition, the land area available for potato production is viewed to implicate RUE. Thus, the combination of various factors such as technology, available resources and environmental conditions have an impact on the measurement of sustainability. It is common in potato production systems to see an over-use of inputs (water and nutrients) by producers due to uncertainty of the optimal amounts required. Therefore, the application of ‘too much rather than too little’ results in economic and environmental vulnerability due to large amounts of resources required.

A problem in the Sandveld region is, due to the very sandy nature of the soil, that all the nutrients are considered leached below the average reported root zone of the potato crop of 30 to 40 cm (Ahmadi et al. 2011). It is even assumed that the nutrients can be lost below the maximum reported root depth of 1 m (Iwama 2008). However, this will not be the case in all regions and greatly depends on the nature and classification of soil forms. Some areas within the Sandveld may contain different layered zones within 1 m of the soil profile, which could lock up ions through chemical reactions or act as a physical barrier slowing down percolation (Hillel 2004). In loamy soils, with a clay content around 15%, more roots are distributed throughout a soil profile and the plant can use nutrients more efficiently during the season (Ahmadi et al. 2011).

2.2 Soil and water

2.2.1 Soil physics

Potato farming systems are viewed to use excessive tillage in comparison to no-tillage or minimum tillage systems often found in the Western Cape. The tillage practices produce low levels of crop residue in a growing year (Carter and Sanderson 2001). Both tillage and low crop residue loads negatively affect soil quality and structure (Aziz et al. 2013; Swanepoel et al. 2015; Swanepoel et al. 2018). Soil structure plays a pivotal role in the movement of water, carbon dioxide and oxygen exchange as well as root penetration. Various processes affect soil structure and include wetting and drying cycles, animal activity and organic or inorganic cementing agents (Scherer et al. 1996). Under potato production systems, due to the destructive nature of required mechanical disturbance during planting and harvesting, coupled with low organic matter and low clay contents, aggregate stability is generally poor and often difficult to maintain (Scherer et al. 1996). Water and nutrient movement within a soil profile is dependent on hydrologic characteristics such as soil-water characteristic curves and permeability function (Rahimi and Rahardjo 2015). An important component of soil water and nutrient movement is soil permeability (Hu et al. 2017). Soil permeability is a physical property of soil influenced by the size, shape and continuity of the pore spaces, which in turn depends on soil structure, texture and bulk density (Scherer et al. 1996). Soil pore spaces can be influenced by compaction. The most susceptible soils to compaction are those with low organic matter, high proportions of silt and clay and that appear to be wet (Johansen et al. 2015). However, sandy soils like those present within the Sandveld region may be compacted because of the formation of weak aggregates. A common contributing factor of compaction is the result of the use of heavy machinery during cultivation, which causes an increase in soil bulk density, a decrease in macro-pore space, and overall porosity, which impedes drainage and can reduce aeration and limit root growth. However, there is limited literature and reports on the effect of soil resistance on root growth in potatoes (Stalham et al. 2007). It is stated by Stalham et al. (2007) that all cultivation equipment causes some form of compaction and any temporary effect on root growth has an impact on soil water and nutrient availability to the roots. In controlled field experiments, there is evidence that reduced yields of potato crops occur due to compaction both in the topsoil and subsoil from the use of heavy machinery (Hatley et al. 2005; Johansen et al. 2015). A series of experiments reported that soil compaction delayed emergence, reduced leaf appearance and ground cover, decreased the duration of canopy cover and negatively affected light interception. All these factors combined will reduce yield (Stalham et al. 2007). For optimal growing conditions, the top 30 to 60 cm of the soil profile for potato production should be loose, moist, relatively free of rocks and excessive plant residue prior to planting (Johansen et al. 2015).

The presence of soil compaction results in the use of rippers, subsoilers and para-ploughs. This can affect the RUE of potato production. A study carried out in sandy soils in potato production systems in Atlantic Canada on the effects of four different tillage practices ranging from conventional tillage to conservation tillage over a three year period indicated that, although soil compaction between 10 to 30 cm increased, it did not reach a level detrimental to root growth and that potato yield and quality were not adversely influenced by tillage practices (Carter et al. 2005). This was in agreement with Carter and Sanderson (2001), who reported that potato yield and quality were similar between various types of tillage and timing of tillage compared to conservation tillage. A significance was however, discovered in the improved soil carbon levels and structural stability of the soil where conservation tillage had been practised in both reports (Carter and Sanderson 2001; Carter et al. 2005). Hopwever, the literature shows controversial results as a study done by Wallace and Bellinder (1989) reported a 22% yield reduction in potato production when reduced tillage was compared with conventional tillage.

2.2.2 Water requirements

Potato is reported to use water relatively efficiently in comparison to other crops (Shahnazari et al. 2007; Vreugdenhil et al. 2011). The crop's water requirement depends on the total seasonal evapotranspiration (ET), which can be reliant on various factors, including irrigation frequency as well as soil matric potential. A study conducted by Kang et al. (2004) noted an increase in potato ET as both irrigation frequency and soil matric potential increased. Haverkort (1982) recommended 400 to 800 mm of water during the growing season for good potato crop growth. Ali et al. (2016) suggested the application of 450 to 600 mm of water in 28 to 30 irrigation events to be made in arid to semi-arid regions. Total water requirements for a potato crop, however, vary in the literature between 190 to 800 mm (Kang et al. 2004; Fleisher at al. 2008; Parent and Anctil 2012). These dissimilar figures arise from the differing climatic regions, soil variability, cultivars, irrigation management and methods as well as how water use is defined. Research into the effect of different irrigation methods on crop yield and water use efficiency (WUE) indicated that for sprinkler irrigated crops the water requirement was between 490 to 760 mm, with trickle irrigated treatments requiring 565 to 850 mm (Unlu et al. 2006). Irrigation method and management play a key role in the efficiency of farming systems. Poor soil water management has been reported to lead to a large difference between actual and potential yield (yield gap) of 20 to 30 t ha^{-1} (Supit et al. 2010).

2.2.3 The role of roots in the uptake of water

A crop's root length and distribution are important factors to consider in agricultural systems in terms of profile wetting depth and the effective rooting depth of the crop. The effective rooting depth is the depth of soil used by the main body of the plant roots to obtain majority of the stored soil water and plant nutrients. The amount of crop-available water is critically dependent on the depth of the effective rooting zone. The effective rooting zone is difficult to estimate or assume, as root systems are very sensitive to soil conditions, which are a factor of both the environment and managerial practices (Greenwood et al. 2010). Due to potato's shallow root system and low capacity to recover after water stress, tubers are susceptible to heat and drought stress (Shock et al. 2007; Iwama 2008; Monneveux et al. 2013; Monneveux et al. 2014). Due to the Sandveld's soil properties having a low nutrient and water holding capacity, soil water levels in the root zone can deplete rapidly. The climatic conditions in the region, particularly in the summer months, result in the root zone temperatures reaching detrimental levels if not managed correctly.

Root development begins before plants emerge from the soil and advance from below ground nodes on the stem. Tuber roots are classified as fibrous and highly branched with adventitious roots forming at the base of the developing sprouts (Cutter 1978; Darling et al. 1977; Wohleb et al. 2014). The root distribution in terms of both depth and density for potato crops has been studied extensively in various countries. There are conflicting views on the temporal pattern of root growth and various rooting depths have been reported for potato crops (Stalham and Allen 2001; Wang et al. 2006; Iwama 2008; Ahmadi et al. 2011). Stalham and Allen (2001) indicated that the majority of root growth was within the top 30 cm of the soil profile. Opena and Porter (1999) also reported the concentration of potato roots within a 30 cm depth. However, another study showed that roots are able to extend up to 1 m in depth (Iwama 2008), depending on various factors such as water and nutrient availability as well as soil texture. Wolfe et al. (1983) reported active potato root growth at a 1.5 m depth. There is little clear evidence to support the assumption that potatoes have shallow root depths as large variations in values are reported in the literature. Root length is known to vary immensely between regions, within regions as well as in the same crop (Iwama 2008). It is however, generally agreed upon that potato crops have a shallower and less dense root system compared to various other field crops (Cutter 1978; Iwama 2008; Wohleb et al. 2014). There are many contrasting root length densities reported. Ahmadi et al. (2011) reported root length density values of 10 to 16 cm cm^{-3}. Iwama (2008) indicated values of 12 to 17 cm cm^{-3} and Parker et al. (1991) reported a value of 10 cm cm^{-3}. The rooting density decreases with depth throughout a soil profile. It is noted that roots deeper down are still able to contribute significantly to crop water requirements, regardless of the soil water content status of horizons closer to the surface (Stalham and Allen 2004). Maximum depth of water extraction is reported to be able to occur at depths of 90 to 120 cm, which can be reached 55 to 75 days after emergence (Stalham and Allen 2004).

2.2.4 Irrigation systems

Potatoes are produced under a number of irrigation methods and systems. A challenging aspect of irrigating in potato production systems in sandy soil conditions is with regards to keeping soil water content at field capacity within the effective rooting zone, due to low water-holding capacities of the sandy soils (Reyes-Cabrera et al. 2016). Root growth is often associated with water movement and availability within a profile and can be manipulated through irrigation techniques. The most common irrigation systems in potato production include seepage irrigation, surface drip irrigation, subsurface drip irrigation, centre-pivot booms, or sprinklers (Deng et al. 2006). Each system has its benefits and issues, but it is known that most irrigation systems do not distribute water uniformly over a field (Ali et al. 2016). Often water application is not adequate to supply the demands of the crop and meet the average soil water deficits (Greenwood et al. 2010). When using centre-pivot systems there is a potential to save up to 55% on irrigated water when compared with seepage irrigation, but seepage irrigation ensures nutrients remain available within the effective root zone for longer (Liao et al. 2016). In another study drip irrigation was shown to be more efficient in contrast to sprinkler and micro jet systems. Surface drip irrigation is reported to have a higher WUE than that of subsurface drip systems. However, no significant advantage can be viewed in implementing subsurface irrigation over surface drip (Onder et al. 2005). Relating irrigation scheduling to plant physiology is key in optimising inputs (Fabeiro et al. 2001). Increasing irrigation management through improved knowledge of physiological growth cycle demands, can increase yields and profit for producers as well as enhance ecological sustainability by negating environmental degradation through over application (Shock et al. 2007). The potato plant is more sensitive to water stress than many other crops, as highlighted by several authors (Shock et al. 1998; Fabeiro et al. 2001; Yuan et al. 2003; Shock et al. 2007). Jefferies (1995) and Epstein and Grant (1973) indicated that in potato production systems, water stress becomes evident when the soil water potential drops below -25 kPa and a value below -45 kPa leads to severe water stress (Kang et al. 2004).

The most susceptible stage to water stress is often argued. Alva (2008) states that the tuber initiation stage is the most critical for water stress, while another report suggests that tuber bulking and ripening are particularly sensitive to water stress (Fabeiro et al. 2001). Irrigation strategies that lead to large water deficit during the stages of ripening, growth or tuber bulking are however, not advisable. Once an understanding of the need for water at varying physiological stages is made then the link between soil properties and climatic conditions on water movement should be acknowledged. The response to water stress is dependent on the soil and climatic conditions found in the location of production and no single recommendation on irrigation scheduling can be provided to all production systems (Alva 2004).

2.2.5 Efficiency of irrigation systems

Irrigation system evaluations are key in determining unnecessary losses of water and to aid the improvement of production with regards to RUE (Ali et al. 2000). For the purpose of this study, only centre-pivot evaluations will be discussed. It should be noted that sprinkler irrigation systems such as centre-pivots apply water more uniformly than surface irrigation methods (Hsiao et al. 2007).

To determine the efficiency of a centre-pivot irrigation system an evaluation must be conducted in order to detect any defects (Ali et al. 2000; Griffiths 2006; Koegelenberg and Breedt 2003). Stewart and Nielsen (1990) reported the factors required to improve irrigation efficiency under varying crops. The most commonly known parameters for evaluation are: application efficiency (AE), the coefficient of uniformity (CU), distribution uniformity (DU), water consumption and distribution uniformity efficiencies (Heermann and Hein 1968; Basheer et al. 2015). Application efficiency is affected by evaporation losses and wind drift as this determines what proportion of the water applied by the system reaches the soil surface. One of the first and most commonly used methods of calculating uniformity is the Christiansen Uniformity Coefficient (CU), developed in 1942. It provides a measure of the average deviation from the mean application depth by measuring the depth of water applied caught by a catch can (King et al. 1999). However, this method was improved upon by Heermann and Hein (1968) who included the distance of each catch can from the centre of the pivot, changing CU to CU_{HH}. Distribution uniformity on the other hand is an indicator of the unevenness of water application and is taken as the percentage of the average application amount in the lowest quarter of the field and is termed (DU_{lq}). The formulas that can be used are described by Ali et al. (2016), using the methods of Christiansan (1942), Merriam et al. (1980) and Asough and Kiker (2002). The distribution of water by a centre-pivot is affected by design and operational factors (nozzle characteristics and operational pressure) as well as climatic factors (wind speed and water droplet evaporation) and management practices (height the sprinklers hang from the soil and crop surface) (Keller and Bliesner 1990; Zhang et al. 2013b). Efficient irrigation is dependent on good uniformity in order to avoid over or under-irrigation to minimise crop variability (Zhang et al. 2013b). However, irrigation can be uniform, but inefficient as reported by Baum et al. 2005.

Ali et al. (2016) concluded that these evaluation parameters could be affected by different operating speeds which determine the water application rate. High operating speeds showed a negative response to DU_{lq} and CU_{HH} however, it showed a positive influence on the AE of centre-pivot systems. Clemmens and Dedrick (1994) reported AE values for well-designed centre-pivot systems to be between 75 and 90%, DU_{lq} values of 78 to 90% and CU_{HH} values of 86 to 94%. Savva and Frenken (2002), who aided the development of the FAO norms, report that CU_{HH} should be >85%. Reinders (2013) presents centre-pivot norms as: CU_{HH} >85%, DU_{lq} >75% and system efficiency >80%. In comparison, maximum CU_{HH} and DU_{lq} values of 91% and 85% respectively, were reported by El-Wahed (2016) when studying the effect of pressure and riser height on DU_{lq} and WUE for sprinkler irrigation systems. Zhang et al. (2013b) also indicated the effect of pressure on CU_{HH} of sprinkler irrigation systems. The results showed that the CU_{HH} decreased rapidly if the pressure was below the manufacturers range and changed very little when within the manufacturers range. The effect of decreased CU_{HH} due to low pressures can also be observed for centre-pivot systems.

2.2.6 Irrigation scheduling

Irrigation scheduling plays a key role in root growth development and distribution throughout the soil profile. Studies that have been conducted on the effects of irrigation frequency and quantity on root growth show that crops irrigated less frequently for parts of the season had deeper maximum rooting depths than frequently irrigated crops (Stalham and Allen 2001; Stalham and Allen 2004) The root structure however, was considerably sparser in terms of root length density. These crops also showed an ability to extract water and nutrients from considerable distances ahead of their root tips. Therefore, it may be viable to assume that maximum rooting depth is not always the maximum depth of water extraction and underestimations are made (Stalham and Allen 2004). However, this is contested by a study conducted by Ahmadi et al. (2011), which concluded that there was no statistical significance between the root length density of partial root-zone drying, deficit irrigation or full irrigation strategies. Stalham and Allen (2004) indicated that partial deficit root zone irrigation did not affect overall crop water use or plant growth, which is in agreement with Saeed et al. (2008). Dalla Costa et al. (1997) and Greenwood (2010) also showed that less water is wasted from excessive drainage and evaporation when partial deficit irrigation was used, compared with full irrigation methods which keeps the root zone near field capacity at all times. However, a study carried out in a semi-arid region in Spain on the effects of deficit irrigation on three different stages of growth namely vegetative growth, tuber bulking and ripening or maturing stages, noted that the effect of water deficit on tuber size and quality was significant during the vegetative growth and ripening stages (Fabeiro et al. 2001), where a water deficit early on during the vegetative growth stage resulted in smaller tubers due to the production of more tubers per plant and therefore, lower mass per unit. Another study, conducted by Badr et al. (2012), indicates a decrease in potato yield when deficit irrigation is practiced. This is attributed mainly to a decrease in tuber mass, as tuber mass is more sensitive than tuber number to deficit irrigation practices. The affected yield in response to this irrigation strategy was observed clearly, when water supply was less than 20% of the crop ET. This advocates that potatoes are sensitive to moderate water deficits and is in agreement with Fabeiro et al. (2001) and Alva (2004), who concluded that deficit irrigation generally showed negative impacts on tuber yield and quality, with the emphasis being on the crop sensitivity during tuber set and tuber bulking (Van Loon 1981). However, a study conducted by Carli et al. (2014) suggests that decreased irrigation and water application after tuberisation resulted in a limited effect on tuber yield and had a positive impact on WUE. Due to the negatives associated with under-irrigating potato crops, over-irrigation often takes place, which increases the potential for disease development, large losses of nutrients through leaching and erosion due to surface runoff (Shock et al. 2007). This is evidence of a need to optimise irrigation to crop water requirements and various techniques used to do this are essential in improving the sustainability of irrigated production systems.

2.2.6.1 Irrigation scheduling practices

Producers generally practice different irrigation strategies and rates according to set schedules and history. Only a few producers in the Sandveld implement scientific methods of calculating ET or soil water content to optimise water use efficiency. Scientific methods determining irrigation amounts and scheduling are at the forefront of improving water use efficiency in agriculture. Irrigation scheduling can be carried out using either atmospheric, plant-based or soil water measurements (Jones 2004). In full irrigation practices, the soil profile to the effective rooting depth is supplied and maintained near field capacity. This practice is often cause of excessive water and nutrient drainage as well as leaching. Deficit irrigation practices on the other hand apply less water than required to meet the crop’s ET demand without reducing crop growth. Deficit irrigation varies according to a specific crop’s sensitivity to water shortages and the stage of growth the crop is in as well as environmental conditions. Sensitivity to water shortages generally occur more during flowering and seed development for various crops. It is generally perceived that deficit irrigation does not affect crop growth unless it inhibits ET. Evapotranspiration remains constant with a decrease in available water until a critical threshold of soil available water is reached. Once the critical threshold is passed, ET decreases linearly with a further decrease in available water until wilting point. In order to understand the crop water requirement, determining water inputs and losses into the cropping system is key and will affect varying irrigation strategies. It is evident that there is a strong correlation between tuber yields and the rate of water consumed by potato ET in a specific location (Bošnjak et al. 2012). Irrigation scheduling can play a pivotal role in preventing unwanted losses of water through ET. An example is scheduling irrigation during the evenings, which is shown to reduce ET losses due to less evaporation and transpiration occurring, allowing sufficient wetting of the soil profile to a suitable depth. (Evans and Sadler. 2008).

2.2.6.2 Reference evapotranspiration, actual evapotranspiration and water availability

2.2.6.2.1 Indirect methods:

2.2.6.2.1.1 Climatological approach

Evaporation refers to the loss of water from soil surfaces, lakes, reservoirs and water intercepted by vegetation. The term transpiration is used in reference to the evaporation of water from within the leaves of the vegetation in question via the process of water vapour flux through leaf stomata (Dingman 1992). Much research has focused on potential evapotranspiration (ET), which refers to the loss of water vapour to the atmosphere via the processes of transpiration and evaporation from the soil's surface or plant surfaces (Allen et al. 1998; Rey 1999; McMahon et al. 2013). Many different definitions regarding ET have been proposed. A review by Granger (1989) identified five definitions however, it was concluded that only three of those five were applicable.

Reference evapotranspiration (ET_o), which refers to the ET of a short grass surface under non stressed conditions where unlimited water supply is available, can be used as an estimate for irrigation scheduling and management (Dingman 1992; Evans and Sadler 2008). Many methods exist in the modelling of ET_o (Table 2.1). All methods incorporate three main concepts: the radiation-based concept, which takes into account solar radiation and temperature; the aerodynamic concept, including humidity and wind speed parameters and the combination equations, which combine the radiation and aerodynamic models. The ET_o can then be used to calculate actual crop ET (AET), which considers soil water status or the number of days after rainfall (Ritchie 1972; Feddes et al. 1978). However, various factors can affect ET, including leaf area index (LAI) and crop height (Rey 1999). A study under a Mediterranean climate by Katerji and Rana (2008) concluded that due to the differing heights of various crops, different responses to air vapour pressure deficit occur. This is agreed upon by Lecina et al. (2003).

Table 2.1. Different concepts used to calculate potential evapotranspiration (ET_o). Modified table from Bormann (2011).

Concept	Authors
Combination equations	Penman (1948)
	Penman-Monteith (1965)
	Rijtema (1968)
Aerodynamic equations	
(Temperature based)	Blaney and Criddle (1950)
	Haude (1955)
	Schendel (1967)
(Wind speed based)	Dalton (1802)
	Trabert (1896)
	Meyer (1926)
	Albrecht (1950)
	Brockamp and Wenner (1963)
	WMO (1966)
	Mahringer (1970)
Radiation equations	Turc (1961)
	Jensen and Haise (1963)
	Ritchie (1972)
	Priestley and Taylor (1972)
	Doorenbos and Pruitt (1977)

Given the arid and semiarid conditions found around the west coast of the Western Cape, the choice of model is crucial (Bormann 2011). However, according to a study conducted by Jensen et al. (1990), which took into account 20 different models to calculate ET_o by analysing lysimeter measurements, the Penman method, which was improved by Monteith (1965), proved to be the superior calculation method which was agreed upon by Kashyap and Panda (2001). The Penman-Monteith model is the most commonly used equation to calculate ET_o from a vegetated surface (Equation (1)). It is often also referred to as the FAO-56 reference crop or standardized reference

ET equation (Allen et al. 1998). However, the Penman-Monteith model is said to suffer from the inability to have correct values for canopy resistance (Katerji and Rana 2006).

$$ET_{p-m} = \frac{1}{\lambda}\frac{\Delta(R_n - G) + \rho_a C_a \frac{(V_a^* - V_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \tag{1}$$

where:

ET_{p-m} is the Penman-Montieth potential evapotranspiration (mm day^{-1});

R_n is the daily net radiation at the vegetated surface (MJ m^{-2} day^{-1});

G is the soil heat flux (MJ m^{-2} day^{-1});

C_a is the specific heat of the air (MJ kg^{-1} $°C^{-1}$);

r_a is the atmospheric resistance to water vapour transport (s m^{-1});

r_s is the surface resistance (s m^{-1});

V^*_a – V_a is the vapour pressure deficit (kPa);

ρ_a is the mean density of the air at a constant pressure (kg m^{-3});

$\boldsymbol{\gamma}$ is the psychometric constant (kPa $°C^{-1}$);

$\boldsymbol{\lambda}$ is the latent heat of vaporisation (MJ kg^{-1});

Δ is the slope of the saturation vapor pressure curve at air temperature (kPa $°C^{-1}$).

A hypothetical reference crop is then adopted using the following parameters: height 0.12 m, albedo 0.23 and surface resistance 70 s m^{-1} (Allen et al. 1998) and Equation (1) becomes Equation (2):

$$ET_{FAO} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_a + 273} u_2(V_a^* - V_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

where:

ET_{FAO} is the daily reference crop evapotranspiration or FAO-56 reference crop evapotranspiration given in mm day^{-1};

T_a is the mean daily air temperature at a height of 1.5 m (°C);

U_2 is the average daily wind speed at height of 2 m (m s^{-1}).

Detailed explanation of reference crop ET and the development of its equation can be found in the literature (Allen et al. 1998; McVicar et al. 2005). The FAO-56 reference crop equation is generally used as the preferred method globally (McMahon et al. 2013). The ET_{FAO} generally differs from the AET of a specific crop under standard growing conditions (McMahon et al. 2013). In order to calculate AET, crop coefficients (K_c) must be taken into consideration.

Crop coefficient values are required for accurate estimations of irrigation requirements for different crops in a specific location (Kashyap and Panda 2001). Crop coefficients play a vital role in providing technical support with regards to saving irrigation water to improve efficiency, specifically in arid climates (Qiufan et al. 2016). Crop coefficients are used to estimate the actual water use of a crop and are expressed as a fraction of the potential evaporative demands (Wright 1982). Various crop coefficients can be calculated either on the basis of the vegetative canopy cover or dual crop coefficients. Canopy cover coefficients were developed by Grattan et al. (1998) and Ojo (2000). However, this method has limitations, as it does not account for the role that soil evaporation plays in the ET of a crop during its early development. Dual crop coefficients on the other hand, as researched by Wright (1982), split the total crop coefficient into soil evaporation and basal crop fractions. The basal crop fraction considers the stage between planting and full canopy cover, where evaporation of the bare soil surface plays a large role and physical characteristics of crops at full canopy cover differ (Ahmed 1997).

There are various methods used to calculate K_c. The K_c values take into account crop characteristics and soil water status (Allen et al. 1998, McMahon et al. 2013). For arid regions, such as the Western Cape, the need to take into deliberation atmospheric advection may need to be conducted. However, Allen et al. (1998) cautions against such practices. A study conducted by Kashyap and Panda (2001) estimated K_c values of a potato crop in a sub-humid region. This was carried out taking the ratio of the daily ET calculated using a direct method from an in-field instalment of a lysimeter and the calculated ET_o computed by different equations that use climatic data [Equation (3)]. The results show that K_c was lowest at the initial growth stage (0.42) and increased constantly up until the reproductive phase, where it reached its highest value 55 to 57 days after planting (DAP) (1.41), it then decreased as the tubers matured. Results obtained by Kashyap and Panda (2001) were in general agreement with the values given by Doorenbos and Pruit (1977) (Table 2.2). In comparison, Allen et al. (1998) suggests the use of much higher values during all the stages of growth, except the reproductive stage. Different crop coefficient values however, have been reported and recommended by various researchers (Table 2.2)

Another method of calculating K_c is through measuring canopy cover or solar radiation interception. Much research has shown that total yield of many crops is related to solar radiation interception (Sibma 1970). Canopy cover and LAI are commonly used to measure light interception and vice versa (Khurana and McLaren 1982; Boyd et al. 2002). Factors such as transpiration, photosynthesis, evaporation and yield are all affected by LAI, which plays a role in the radiation interception throughout crop growth (Gordon et al. 1997). Light interception of a crop's canopy is dependent upon its LAI (area of leaves in m^2 per area of soil in m^2), which consecutively regulates the percentage of the soil covered by green leaves. There is a strong correlation between the percentage of light intercepted, LAI and the percentage of ground covered by green leaves (Haverkort 2007). Haverkort et al. (2015) reports a linear relationship between LAI and light interception between LAI values of 0 and 3, with 100% light interception at a LAI of ≥3 and none at a LAI of 0. The LAI of ≥3 corresponding to 100% ground cover by potato crops was previously reported (Haverkort et al. 1991). However, Wright (1982) reported the use of 3.5 at 100% canopy cover. The percentage canopy cover calculated using LAI could then be used as a crop factor to estimate crop ET (Equation (5)). Light interception can be measured with a ceptometer or remote sensing. Various research has indicated that at the stage of maximum leaf area expansion, radiation interception efficiency is at its optimum (Haverkort et al. 1991). Scott and Wilcockson (1978) were the first to relate light-use efficiency to the total amount of dry matter accumulation in potato (DM), which has extensively been researched (Khurana and McLaren 1982; Kabat et al. 1995; Kooman and Haverkort 1995; Haverkort 2007). The rate of leaf expansion is determined by temperature. Solar-radiation readings can be used to calculate LAI using the Lambert-Beer equation [Equation (4)] (Tarkalson et al. 2012). Haverkort et al. (1991) concluded that canopy cover determined for a crop is an accurate method to estimate solar radiation interception. This statement disputed earlier findings by Firman and Allen (1989), who indicated that canopy cover should not be used to measure light interception, as it does not consider the effect that the density of the canopy has on light interception. They concluded that in order to estimate light interception, LAI is the more accurate canopy measure. Boyd et al. (2002) indicated that canopy cover and the percentage light interception calculated using the Lambert-Beer law was exceedingly more interrelated than ground cover and LAI within potato production systems. However, there was still a high correlation between LAI and ground cover, even under differing management practices. The percentage soil cover by green leaves can ensure an acceptable estimation of intercepted radiation (Burstall and Harris 1983). This can also be carried out using the standard grid method as described by Burstall and Harris (1983).

The use of ceptometers to measure fractional interception of photosynthetically active radiation (PAR) by the canopy is recommended. However, it is more costly than the use of solarimeters, which measure total solar radiation (Haverkort 2007). The assumption that above and below canopies spectral composition are insignificant with the use of solarimeters must be made. The solarimeters however, tend to overestimate values as it does not distinguish between green and brown leaves as well as stems.

$$K_c = \frac{ET_c}{ET_0} \tag{3}$$

$$I = I_o e^{-k(LAI)} \tag{4}$$

$$ET_c = ET_o \times \left(\frac{LAI}{3}\right) \tag{5}$$

where:

I signifies below canopy solar radiation readings (ground level);

I_o represents above canopy readings solar radiation readings;

k is the light extinction coefficient.

The light extinction coefficient or radiation extinction coefficient refers to the efficiency with which a crop's green leaf area intercepts solar radiation (Muurinen and Peltonen-Sainio 2006). It has been reported to have differing values in various locations. A value of 0.4 has been reported in the literature (Khurana and McLaren 1982; Burstall and Harris 1983; Haverkort et al. 1991). However, more recent research conducted by Zhou et al. (2016) and Zhou et al. (2017) in a temperate climate within Denmark estimated *k* as 0.72. Haverkort et al. (2013) reported the use of the extinction coefficient value of 1 in Southern Africa.

The relationship between LAI and light interception can be quantified by the extinction coefficient (Monsi and Saeki 1953). When crops have canopies with larger extinction coefficients, a loss in LAI will have a smaller effect on the fraction of light interception, compared to a crop with a lower extinction coefficient (Fletcher et al. 2013).

Table 2.2. The crop coefficients of potato crops reported in various studies. Modified table from Parent and Anctil (2012).

Studies	Growing season average	Seedling	Sprout development	Vegetative growth	Tuber initiation	Tuber bulking	Maturation
Doorenbos and Pruitt (1977)	0.78	-	0.50	0.80	-	1.10	0.72
Hane and Pumphrey (1984)	-	-	0.30	-	-	0.80	-
Allen et al. (1998)	0.92	-	0.80	0.98	-	1.15	0.75
Kashyap and Panda (2001)	0.78	-	0.42	0.85	-	1.27	0.57
Allen and Wright (2002)	0.51	0.20	0.31	0.64	0.77	0.73	0.36
Karanja (2006)	0.80	-	-	-	-	-	-
Sahin et al. (2007)	0.60	-	-	-	-	-	-
Ferreira and Gonçalves (2007)	0.86	-	-	-	-	-	-
Bos et al. (2009)	-	-	-	-	-	1.15	0.35
Siebert and Döll (2010)	-	-	0.35	-	-	1.15	0.50
Parent and Anctil (2012)	0.73	0.27	-	0.63	0.91	0.81	0.78

2.2.6.2.1.2 Water balance

A method for estimating soil water availability to crops throughout the season is through conducting soil water balances (SWB). This method is based on the ideologies of conservation of mass in a one-dimensional degree within a crop's effective rooting zone (Lazzara and Rana 2010). It can be used as an indirect method of calculating ET (Lazzara and Rana 2010). It is a method mainly used in irrigated crop production systems (Parent and Anctil 2012). Soil water balances can be used as an important tool to improve water use efficiency. However, accuracy of various models is placed under scrutiny and there is a need to closely evaluate each model within a range of cropping systems and its viability within a certain region, or specific location within a region. It is often problematic to quantify all components of the method accurately. Therefore, simplifications are often made (Lazzara and Rana 2010). For example, capillary rise is often neglected when there is no shallow water table present and on a flat topography, surface runoff can be considered negligible.

The SWB is made up of various components. The main components include soil water dynamics and ET. Soil water dynamics are often calculated using the 'tipping bucket' approach or Richards equation. Indirect methods include climatological parameters as the input into various equations. There are various models, with the ability of calculating a water balance, that use varying components as their input parameters. Adaptation of models are conducted in order to best suit a particular environment or location. It can be noted that various potato models, in particular, have been adapted from systems that were initially created for maize (*Zea mays*) or cereal crops (Paredes et al. 2018). Models therefore have varying structures, disparate approaches and focus on differing procedures (Paredes et al. 2018). However, they can be regarded as an essential tool in determining crop available water as well as ecological impacts caused by nutrients (Soldevilla-Martinez 2013). Due to growing concerns regarding the over-application of water and the increased limitation of its availability as a resource in certain regions, models can be used to advise producers in irrigation scheduling throughout growing seasons in order to optimise WUE and provide decisions towards the economic feasibility of irrigation equipment (Haverkort et al. 2015). Many potato and other crop models exist. A review by Raymundo et al. (2014) reports the availability of over 30 models for potato production systems, with a few of those models being more specific for sweet potato production (*Ipomoea batatas*).

Modelling the SWB can vary according to parameters present, but all possess the same fundamentals. The fundamentals being a balance between water inputs irrigation (I), rainfall (P) and to little effect capillary rise (C_r), as well as water lost through ET, run-off (R) and drainage (D). Change in soil water content ΔSWC taken from the difference between the final soil water content (W2) and the initial soil water content (W1). Different variations of the water balance are present, as illustrated by Equation (6) (McMahon et al. 2013), Equation (7) (Parent and Anctil 2012) and Equation (8) (Hillel 2012; Hanks and Ashcroft 1980). A major source of error with the SWB method is the difficulty to establish deep drainage measurements (Farahani et al. 2007). Assumptions often have to be made when using the water balance application. Often, unless a shallow water table is present, C_r is considered negligible along with runoff if the crop is grown on a flat terrain or sandy soil profiles are present, as these are associated with high infiltration capacities (Parent and Anctil 2012).

$$P = ET + R + \Delta SW \tag{6}$$

$$\Delta SWC = I + P + C_r - ET - R - D \tag{7}$$

$$AET = (W1 + P + I) - (W2 + D + R) \tag{8}$$

2.2.6.2.2 Direct methods:

2.2.6.2.2.1 Weighing lysimeter

Evapotranspirometers (mainly referred to as weighing lysimeters) have been used for over 300 years (Howell et al. 1991; Lazzara and Rana 2010). Weighing lysimeters have been extensively developed and researched in the last 80 years for the measurement of ET (Howell et al. 1991; Schneider et al. 1998; Xu et al. 1998; Clawson et al. 2009). Only a weighing lysimeter can be used to determine ET directly using the mass balance of water. A non-weighing lysimeter can only be used to indirectly determine ET from the volume balance (Howell et al. 1991). The weighing lysimeter in the research of well-watered crops is often considered the reference technique to test other ET measurement methods. The precision of weighing lysimeters in measuring ET is reported between 0.05 to 0.02 mm (Howell et al. 1991). However, ET accuracy depends on various factors such as crop height, cultivation practices as well as the structure of the lysimeter. A severe limitation as stated by Wegehenkel and Gerke (2013) is that in high radiation climates, such as those present in regions with Mediterranean-type regions, like the Sandveld, there can be an overestimation of ET due to an oasis effect. The oasis effect is a result of differing thermal regimes occurring between the lysimeter and surrounding soil. This effect is however, dependent on the spatial gap between the soil and lysimeter.

2.2.7 Drainage and soil water movement

Deep drainage or soil water flux is seen as an important process in ecosystems as it removes excess soluble salts from plant root zones and provides ground water recharge. However, it also affects the efficiency of agricultural systems, especially where irrigation is occurring. An understanding of deep drainage in agricultural systems will allow the adaptation for more efficient farming practices (Gunawardena et al. 2011). Gee et al. (2009) stated that there is no standard method to measure soil water flux. Their study concluded that direct measurements of water flux are principally restricted to lysimeters. Allison et al. (1994) studied various methods, direct and indirect, to determine ground water recharge. The study concluded indirect estimations such as Darcy's flux measurements and the SWB are the least effective. Direct methods such as tracer methods were reported to be the most effective, particularly in arid regions and lysimeter methods were particularly useful in coarse textured soils. Indirect estimations can be carried out by measuring certain soil characteristics. This can be done using tensiometers, frequency domain reflectometry, time domain reflectometry heat-pulse probes, electrical resistivity topography, and ground penetrating radar, to name a few (Weihermüller et al. 2007; Meissner et al. 2010).

2.2.7.1 Direct methods of measuring soil water movement and drainage

2.2.7.1.1 Drainage lysimeter

Drainage lysimeters (also known as volume lysimeters) are based on the concept of volume balance (Howell et al. 1991). The Greek words *lysis* and *metron*, from which lysimeter is derived, means to 'measure movement' (Aboukhaled et al. 1982). They are made up of a rectangular or circular container placed within the soil profile to measure vertical water movement (Howell et al. 1991). Lysimeters vary in size and dimensions according to their use, however, it was cautioned by Kohnke et al. (1940) that no one-lysimeter structure should be considered standard and the design should be adapted according to the required outputs, climatic, pedological and geological conditions. There is much debate regarding the shape of lysimeters and the different shape uses (Duncan et al. 2016). Circular lysimeters are much more robust, but the representativeness of the surface area in comparison to row crop geometry is often questioned (Howell et al. 1991). Rectangular shaped lysimeters are more commonly used for weighing lysimeters, but the width must take into account the row spacing of crops (Howell et al. 1991). There are various reports available on the efficiency of differing lysimeter models along with their advantages and disadvantages (Zhu et al. 2002; Masarik et al. 2004; Arauzo et al. 2010). Due to lysimeters being placed in a singular location within a field, representation of entire field conditions is questioned as soil uniformities vary within given plots. However, Gu et al. 2014 reported that they can be considered sufficiently representative of field parameters. It is conveyed that drainage lysimeters are suitable for long-term measurements as they rely on physical and not chemical methods (Gunawardena et al. 2011). In previous years a major issue with drainage lysimeters has been the process of preferential flow along the side walls of the structure, however in recent years this has been overcome in models such as the passive capillary lysimeter or Gee passive capillary lysimeter (Corwin 2000). Various field methods to quantify soil water drainage have been studied, with reports of passive capillary lysimeters giving better estimates (Gee et al. 2002; Jabro et al. 2008).

The first equilibrium tension lysimeter, which the passive capillary lysimeter is based upon was developed by Brye et al. (1999). This device was developed to maintain the equilibrium between the lysimeter and soil mass. Masarik et al. (2004) improved this design by introducing an automated tension control system to mimic the soil water matric potential within the soil profile. This was further improved upon by Gee et al. (2003) who placed a divergence control tube over the wick in order to minimize water divergence. In previous studies, it was noted that when determining nutrient leaching from the soil, errors in the measurement of drainage and nutrient concentrations would occur. This was suggested to be an issue when using the widely implemented porous ceramic suction cup samplers, which result in the modification of the soil solution chemical composition during extraction (Marques et al. 1996). Marques et al. (1996) stated that ceramic suction samplers should not be implemented in the extraction of soil solution for chemical analysis. Due to the passive capillary lysimeters ability to only collect drainage water, it is able to eliminate contamination and is suitable for nutrient chemical analysis of drainage solution. (Arauzo et al. 2010). Arauzo et al. (2010) studied the efficiency of leachate collection from a Gee passive capillary lysimeter on alluvial soils and obtained results of 101 ± 1% (mean ± standard deviation). These results coincided with those reported by Zhu et al. (2002) in tilled and untilled plots on silty loam soils. However, Van der Velde et al. (2005) disagreed with these reports and concluded that wick lysimeters overestimate drainage under tropical conditions.

Kim et al. (2011) conducted a study on the accuracy of sensors within a passive capillary lysimeter compared to actual drainage collected by suction pumps. The study concluded that lysimeters closely matched sampled drainage water with an r^2 value of 0.95. The same study observed the effect of different irrigation strategies (frequency) used, on potato, sugar beet and malting barley and the effect this had on drainage accumulation. Results showed that low irrigation frequency (30 mm per irrigation cycle) gave rise to larger amounts of drainage accumulation than a higher irrigation frequency (15 mm per irrigation cycle). The explanation being that there was an increased potential of water loss via the processes of evaporation and transpiration before water movement into the root zone of the crop in more frequently irrigated plots.

The placement of drainage lysimeters should typically take place in the soil profile where it will not impede root growth. Installation is considered one of the harder processes and can lead to the modification of the soil around the lysimeters location, which may in turn lead to the process of preferential flow and alter the soils natural drainage (Arauzo et al. 2010).

2.2.7.1.2 Suction cups

Hart and Lowery (1997) described various types of suction cups as well as their advantages. They are also known in the literature as porous tubes, suction lysimeters or pressure vacuum lysimeters (Parizek and Lane 1970). This equipment can measure nutrient contents of soil water in the profile at various depths. However, the flux of water past the device is not measured. Installation of this type of equipment is very simple and easy (Weihermüller et al. 2007). A negative pressure is required for the operation of these devices and is created by a vacuum pump. Water is then extracted via capillary suction which is the action that causes water from moist soil to move into the pores of the suction cup. The water is then held by a suction which causes the cup to become sealed from the pressure of the air allowing a vacuum to be drawn into the suction cup, resulting in the movement of water from the soil into the cup, if the tension in the soil becomes less than 1 atm (101.325 kPa) (Parizek and Lane 1970). There is however, conflict on the optimum height of applied suction (Brandi-Dohrn et al. 1996; Weihermüller et al. 2005). Weihermüller et al. (2005) concluded that suction applied is dependent on soil parameters and soil water content. Conjecture has been made by Hansen and Harris (1975) that suction cups have a predilection for monitoring chemical conformation of larger soil pores to the expenditure of smaller soil pores. Other negatives associated were reported by Jiménez et al. (2013) with regards to limited sampling size and the ease of potential contamination of samples.

2.2.7.2 Indirect methods of measuring soil water content, movement and drainage

Various sensors such as tensiometers, capacitance probes and resistance blocks are available for the determination of soil water content or soil water potential and have been researched expressively (Morgan et al. 2001; Nolz et al. 2013). The difference in measurement of SWC should not be preferred over soil water potential and vice versa as the ability of a given soil to supply water to plant roots is governed by both SWC and potential (Greenwood et al. 2010). Concerning irrigation requirement, the soil water retention curve is required to measure the missing parameter, no matter which sensor is preferred (Greenwood et al. 2010).

2.2.7.2.1 Soil water content

Soil water content is directly proportional to the dielectric constant, which is dependent on the electrical resistivity of a soil. Electrical resistivity has been extensively researched (McCarter 1984; Chen et al. 2010; Parsons and Bandaranayake 2009; Muñoz-Castelblanco et al. 2011; Pandey et al. 2015). Dielectric sensors or capacitance probes such as frequency domain reflectometry and time domain reflectometry have been studied extensively (Fares and Alva 2000a; Bello et al. 2019). Advantages of these sensors are their low cost, non-destructive installation and high accuracy (Bello et al. 2019).

The dielectric constant of the soil is strongly dependent on the polarization of its molecules and is correlated to the change in soil water content (Fares and Alva 2000b; Wu et al. 2011). This correlation is reliant on soil-type and the frequency range of the device (Fares and Alva 2000b). However, various researchers concluded within a wide range of soil types, that the capacitance probe method is independent of soil type (Hoekstra and Delaney 1974), as the volumetric water content and electrical value (calibration curve) is generally linear for the majority of soils (Mead et al. 1995). This was disputed by Kuraz and Matousek (1977) and Bell et al. (1987). The two studies concluded that soil bulk density and type influenced capacitance probes significantly. A study by Bello et al. (2019) concluded that clay loam soils had linear calibration functions compared to polynomial functions required for sandy loam soils. So, the recommendation of calibration for differing soil types can be justified to improve accuracy of measurements (Varble and Chávez 2011). Careful consideration of calibration methods should take place as factory calibration recommendations have been reported by various studies to not achieve required accuracies (Malazian et al. 2011; Varble and Chávez 2011; Nolz et al. 2013). Therefore, the recommendation of site-specific calibrations can be made (Geesing et al. 2004). It is well studied that within soils there is a decrease in electrical resistivity with an increase in water content (Muñoz-Castelblanco et al. 2011; Piegari and Maio 2013; Pandey et al. 2015). The dielectric value of water is 80 compared to that of soils, which is between 2 and 5. Therefore, more water results in a higher dielectric constant (Morgan et al. 2001). Due to sandy soils' low water holding ability, its total water content and dielectric constant are low, even at field capacity. The water holding ability of sand at field capacity is generally low (<0.10 m^3 m^{-3}) (Parsons and Bandaranayake 2009). Bandaranayake et al. (2007) reported a field capacity value, for Entisol soils containing >95% sand, of 0.08 m^3 m^{-3} which coincides with what was reported by Obreza et al. (1997). Research has showed that dry sands have a very high electrical resistivity (Muñoz-Castelblanco et al. 2011). A study conducted by Pandey et al. (2015) concluded that an increase in SWC in sandy soils decreased the soil's electrical resistivity. This was also reported in a previous study (McCarter 1984). However, the rate of decrease reduced significantly for water contents over 10%. Resistivity was also found to decrease linearly with an increase in the soil's relative density, but this relationship was found to be negligible at higher water contents. At a water content (>16%) sandy soils showed a constant resistivity. However, a main concern with the dielectric method and the use of sensors working on the concept of time domain reflectometry is in the application of fine-grained soils, where a dielectric dispersion may occur due to water situated within particle aggregations in clays (Cosenza and Tabbagh 2004).

2.2.7.2.2 Soil water potential

Literature empathizes the relationship between soil matric "suction" potential and SWC. This relationship is referred to as the soil water characteristic curve (SWCC) or sometimes termed the soil water retention curve (SWRC) (Fredlund 2002; Masrouri et al. 2008; Malaya and Sreedeep 2011; Toll et al. 2013; Aldaood et al. 2015). The SWCC is dependent on soil texture and porosity as well as many other factors (Suriya et al. 2015). As soil suction decreases soil volumetric water content increases (Singh and Kuriyan 2003). In-field use of SWCCs for the estimation of suction is discouraged due to the effect of hysteresis associated with drying and wetting (Fredlund et al. 2011; Iiyama 2016). However, the use of SWCCs to measure suction produce a smaller percentage error in sandy soils than in clay soils, as reported by Fredlund et al. (2011). Tensiometers and resistivity sensors are common devices used to measure soil matric potential (Singh and Kuriyan 2003). The usefulness of tensiometers to measure soil suction potential is reported by Singh and Kuriyan (2003). They are often used in irrigation scheduling as they are easily managed and provide a reliable measurement of soil water status and the energy required by plant roots to absorb water from soil (Maddah et al. 2014). The total energy at which the soil holds onto water can be split into two groups: the matric potential (including capillary suction) and osmotic potential (including solute suction) (Richards 1974; Masrouri et al. 2008). Osmotic potential is present in soils influenced by high plasticity clays or due to the presence of dissolved salts (Blatz et al. 2008).

Tensiometers were first developed in the 1900's by Richards (1928) with the design and shape commonly known today, as reported by Tarantino et al. (2008). In the 1970's and 80's tensiometers able to measure a suction of 0 to 40 kPa were made available (Tarantino et al. 2008). However, developments by Ridley and Burland (1995) introduced a tensiometer that can measure suctions up to 1 500 kPa, which is considered the permanent wilting point of plants (Tarantino and Mongiovi 2003). Therefore, up until recently tensiometers had a limited range in measuring suction (<90 kPa) (Tarantino et al. 2008). Tensiometers have been reported in the literature to be useful for measuring soil suction between a range of 0 to 100 kPa (Blatz et al. 2008; Mendes et al. 2008). Bulut and Leong (2008) reported difficulty in measuring suction below 100 kPa. However, a study by Toll et al. (2013) reported that under the use of high suction tensiometers, direct measurements of up to 2 500 kPa could be made, but with most measurements in soils being limited to 1 000 kPa. The possible use of high suction tensiometers within field applications was also reported by Cui et al. (2007).

Nolz et al. 2013 conducted a study on two different types of sensors measuring soil water potential. The study concluded that the Decagon manufactured MPS-1 had a larger sensor to sensor variation than the Watermark sensor (Irrometer Company, Inc. Riverside California, America). The recommended factory calibration was also reported to give inaccurate results. This was also suggested to be an issue in a study carried out by Malazian et al. (2011), where optimised common calibrations had to be developed. Morgan et al. (2001) concluded that the effective range of Watermark resistance blocks and tensiometers in sandy soils to be between -5 and -20 kPa. An issue arising with the use of tensiometers is if air bubbles form in the tensiometer reservoir, re-pressurization or a suction must occur which requires their removal (Toll et al. 2013). However, Mendes et al. (2008) reported that tensiometers can be left in field for long-term measurements. Parsons and Bandaranayake (2009) also concluded that sensor to sensor variation can be an issue in soils with a narrow water content range. Another negative with regards to the use of standard tensiometers is the delay in response to pore water pressure change (Evans and Lam 2002).

2.3 Water-use efficiency

Water availability has a strong impact on RUE in agricultural cropping systems. A method of determining the efficiency of water in a production system is through the calculation of a crop's WUE. There is debate and confusion regarding the term "*water use efficiency*" and its preferred definition. The application efficiency is generally associated with system operations. Therefore, its use in the agricultural sector can lead to much debate. Water use efficiency is often defined as the increase in crop productivity per unit of water consumed or used (Fabeiro et al. 2001). However, this term contains a few drawbacks as we refer to it as a biological response ratio and not an efficiency term (Evans and Sadler 2008). The term WUE was criticised by Monteith (1993) as having no theoretical limits as a reference, which would be the case if efficiency were regarded from an engineering perspective. The term refers more to crop performance than to water conservation. Hence, a more suitable term for the subject at matter may be crop water productivity. Water use efficiency in potato production is generally expressed as the ratio of tuber yield to ET (Table 2.3) (Nagaz et al. 2007; Fleisher et al. 2008).

Table 2.3. Different methods used to calculate water use efficiency in potato production systems.

Concept	Authors
$WUE = \frac{Y}{(I + P + \Delta S)}$	Ahmadi et al. (2010); Jia et al. (2018)
$WUE = \frac{Y}{Total\ water\ used}$	Ali et al. (2016)
$WUE = \frac{Y}{ET}$	Kang et al. (2004); Evans and Sadler (2008); Nagaz et al. (2007); Fleisher et al. (2008); Li et al. (2018a)
$IWP = \frac{Y}{I}$	Darwish et al. (2006); El-Abedin et al. (2017)

where:

Y is the fresh tuber yield or dry matter in kg ha^{-1};

I is the water applied through irrigation (mm);

P is the amount of precipitation (mm);

ΔS refers to the change in soil water storage between planting and harvest (mm);

Values of WUE can be reported in kg mm^{-1}, kg m^{-3} or kg ha^{-1} mm^{-1}.

Howell et al. (1991) indicated the difficulty in measuring ET and suggested the use of other methods. Other methods include calculating the ratio of tuber yield to water applied through irrigation and precipitation (Xie and Su 2012). However, Darwish et al. (2006) demonstrated the use of irrigation water productivity (IWP) also termed irrigation water use efficiency (IWUE), which gave much higher results than WUE due to the neglect of the effect of unpredictable rainfall. Water use efficiency and IWP are parameters that can be improved through either increasing yields or decreasing water applications to crops whilst maintaining consumer quality or a combination of both (Badr et al. 2012). Unfortunately, the mentality regarding maximising WUE is often only a goal under water scarce conditions. However, it is believed that an increase in WUE in the agricultural sector will aid the mitigation of water shortages and environmental degradation (Deng et al. 2006). In order to optimise WUE a clear conceptual understanding of soil water movement and distribution under a crop, with relevance to effective rooting depth and crop requirement is requisite (Robinson 1999). In general, the potato plant uses water relatively efficiently (Monneveux et al. 2013), but yield and tuber quality are particularly susceptible to soil water deficits (Sharafzadeh et al. 2011). A factor significantly affecting water uptake in potato crops is root growth, as indicated by Liao et al. (2016) that potato yields are controlled by the soil water status in the top 20 to 30 cm of the soil profile. Its shallow root system results in poor suction capacity and if soils become too dry, water becomes the most limiting factor (Sharafzadeh et al. 2011). To sustain potato production and yields it is not recommended to let the soil water potential drop below -20 kPa (matric potential) within the rooting zone (Bailey 1990). Therefore, deficit irrigation is not a recommended practice for potato production. Irrigation is not the only factor affecting WUE, as a study by Ierna and Mauromicale (2018) showed. They concluded that WUE was negatively influenced by irrigation and positively enhanced by fertilisation. Both low and medium fertiliser rates (NPK: 50, 25, 75 kg ha^{-1} and 100, 50, 150 kg ha^{-1}, respectively) allowed maximising water use when plants where irrigated 25 mm at plant emergence only.

2.3.1 Factors affecting water use efficiency

Many factors such as soil texture, crop variety, root growth and distribution affect the WUE of a crop (Katerji and Mastrorilli 2009; Ahmadi et al. 2010; Ahmadi et al. 2014). Kang et al. (2004) concluded that potato WUE was affected by both soil matric potential and irrigation frequency. In their study lower application rates applied more frequently resulted in a higher WUE. They also reported that the highest WUE was obtained at a soil matric potential of -25 kPa and an irrigation frequency of once a day. Wang et al. (2006) also concluded that a relatively high irrigation frequency enhanced WUE as well as potato yield and a reduction in irrigation frequency showed significant decreases in yield. Irrigation technique also plays a major role in the WUE or IWP of crops. El-Abedin et al. (2017) concluded that in potato cropping systems full irrigation techniques produced the highest IWP, followed by deficit irrigation and then partial root zone drying. For potatoes, similar results were reported by Liu et al. (2006) and Ahmadi et al. (2014). This contradicts reports by Jovanovic et al. (2010) that in potato production, higher IWP values were obtained when partial root zone drying irrigation was practiced compared to deficit irrigation. This suggests controversial reports in the literature. Management practices also play a role in WUE, as shown by Zhao et al. (2014) in a rainfed agricultural system in China. This study reported the benefits of ridge-furrow full plastic mulching on WUE and potato yields. Water use efficiency values ranged between 16.7 and 20.4 kg ha^{-1} mm^{-1} for full plastic mulching. This is in agreement with Li et al. (2018b). Li et al. (2018b) reported an increase in WUE under plastic mulching (28.7%) and straw mulching (5.6%). This was particularly evident in potato cropping systems applied with <400 mm of water. The effect of mulching on increased WUE or IWP is due to decreased soil evaporation, warmer topsoil temperatures and increased water holding. Another study by Li et al. (2018a) concluded that compared to no mulching, plastic mulching increased WUE by 31.7%. Katerji and Mastrorilli (2009) showed the effect of soil texture on WUE. It was concluded that there was a decrease in WUE for potato, sunflower, maize and sugar beet when grown in clay soils. Water use efficiency values in clay and loam for potato were reported at 16.1 and 21.0 kg m^{-3} respectively. Water use efficiency and IWP values differ around the world and between crops. In China, typical WUE values of 0.46 kg m^{-3} for potato were reported (Deng et al. 2006). To show the difference in WUE of various crops, Hu et al. (2001) reported values of grasses at 0.26 to 0.41 kg m^{-3} and shrubbery at 0.28 to 0.32 kg m^{-3}. Nutrient application has also been shown to influence the WUE of crops. A study on the interaction of fertigation on nitrogen (N) use efficiency by Jia et al. (2018) concluded that drip fertigation increased both WUE and N use efficiency 1.4 to 2.0-fold and this practice can be recommended on sandy soils. Darwish et al. (2006) reported IWP values of 7.7 to 8.6 kg m^{-3}. This is similar to values stated by Darwish et al. (2003). Duan and Zhang (2000) in a study in China reported WUE values for wheat (*Triticum* spp.; 0.8 – 1.32 kg m^{-3}), Maize (1.70 – 1.74 kg m^{-3}), sorghum (*Sorghum* spp.; 1.91 kg m^{-3}) and soybean (*Glycine max*; 0.57 kg m^{-3}) under irrigation. In contrast, a study in Southern Libya by El-Wahed (2016) reported a WUE value of 0.75 kg m^{-3} for barley (*Hordeum vulgare*) under sprinkler irrigation. This study indicated the effect of operating pressure and sprinkler heights on WUE. An operating pressure of 200 kPa, 250 kPa and 300 kPa produced WUE values of 0.39, 0.52 and 0.68 kg m^{-3} respectively, with sprinkler heights of 100, 125 and 150 cm producing WUE values of 0.48, 0.52 and 0.59 kg m^{-3} respectively. From this it was concluded that higher sprinkler height and operating pressure increased WUE. A previous study conducted by Steyn et al. (2016) reported an average of 78 kg mm^{-1} for potato production in South Africa, so generally, anything ≥78 kg mm^{-1} is acceptable.

2.4 Fertilisation

2.4.1 Nutrient use efficiency

Research into nutrient use efficiency (NUE) is imperative in the move towards more sustainable production systems, particularly in locations where soils have low nutrient holding capacities. Given the adverse economic and environmental impacts of excessive nutrient application, particularly associated with N and P, it is imperative to research nutrient use efficiencies to minimise detrimental impacts on the environment (Fageria et al. 2008). The potato crop is a nutrient responsive plant. However, when shallow-rooted crops are grown on sandy soils, excessive use of nutrients can potentially result in environmental damage and high production costs. The improvement of NUE can thus be used as a strategy to address the issue of sustainability and improve yields (Tiwari et al. 2018).

Nutrient use efficiency refers to the portion of nutrient taken up by the crop as a percentage of applied nutrient. However, studies on the NUE of potato crops have been limited to agronomic practices or soil management and ecological as well as physiological concepts have been neglected (Tiwari et al. 2018). In potato production, most research emphasises on improving site-specific fertilisation efficiency through nutrient management in the soil (Zebarth and Rosen 2007). Much of the research is specific to N use efficiency, but the methods can be utilised for all nutrients (Kutra and Aksomaitiene 2003; Weih et al. 2011; Hu et al. 2014; Swain et al. 2014; Gitari et al. 2018; Tiwari et al. 2018). The different terms and calculations used are described by Tiwari et al. (2018). This study also reports NUE of potato crops to be best defined as the tuber yield obtained per unit of nutrient supply (fertiliser and residual). Moll et al. (1982) reports nutrient use efficiency as the total plant nutrients taken up at maturity per unit of nutrient supplied from fertiliser and mineral N. However, they assume that throughout the crop growth cycle, from planting to harvest, any nutrient (they referred to N) is available, which creates conceptual issues. The study concludes that nutrient uptake efficiency (NU_pE) and nutrient utilisation efficiency (NU_tE) should be considered as they form important components in the overall NUE throughout crop growth. In research conducted by Gitari et al. (2018) on the uptake of N and P in potato intercropping systems, the calculations of plant nutrient uptake were taken as the sum of the product of the plant tissue dry mass and nutrient concentration. The NU_pE was calculated as the ratio of the total plant nutrient uptake and nutrient supply. This coincides with the methods used by Errebhi et al. (1998), Zebarth et al. (2004), Kołodziejczyk (2014) and Tiemens-Hulscher et al. (2014). However, the calculation of NUE by Gitari et al. (2018) was conducted with the inclusion of potato equivalent yield, which considers the market price of potatoes.

There are numerous terms and methods determining NUE, but the outcome is aimed to provide information on strategies to improve NUE in cropping systems. Improving the NUE of cropping systems can be established through decreasing nutrient application whilst maintaining yields or by increasing both yield and nutrient application (Tiwari et al. 2018). Other methods include gene manipulation, selective breeding i.e. enhancing photosynthetic capacity by manipulating Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCo) activity (Weih et al. 2011).

The look into the macro elements and their impact on the potato cropping system will aid understanding of nutrient-soil-plant interactions and the best management practices needed to ensure an economically and environmentally sustainable system.

2.4.2 Nitrogen

Nitrogen (N) is the most limiting nutrient in potato production, especially when cultivation occurs on sandy soils (Munoz et al. 2005). The effect of N on tuber yield has been extensively researched (Bélanger et al. 2000; Kavvadias et al. 2012; Hu et al. 2014; Van Dingenen et al. 2019). However, the response of various fertiliser application rates is cultivar dependant (Van den Berg et al. 1996; Mokrani et al. 2018). If N is available to the plant at high rates, there is a positive response on both vegetative growth and light interception (Oliveira 2000). Therefore, farmers often apply N at higher rates than the minimum requirement (Lemaire and Gastal 1997). N stress in potato has negative impacts on photosynthesis and the partitioning of assimilates (Jin et al. 2015).

2.4.2.1 Nitrogen source (ammonium vs. nitrate)

Potatoes prefer N in the form of nitrate (NO_3^-), instead of ammonium (NH_4^+). Current research is targeting improved NU_pE in potato production systems with emphasis on reducing excess leaching of nitrate into water sources (Davenport et al. 2005). There are two notable processes defining NU_pE: the plant's ability to absorb N from the soil and its ability to convert that N into a usable form within its organs (Saravia et al. 2016). The high solubility of nitrate in water means the ion will not be easily adsorbed by soil colloids or organic matter, which is commonly present in low concentrations in potato production systems due to the nature of the soil profiles used as growth mediums. The uptake of nutrients goes hand in hand with the distribution and quantity of water applied to the soils, therefore irrigation and nutrient management are likely to be correlated. A study carried out by Saravia et al. (2016) shows the importance that water plays in NU_pE and that N uptake is reduced greatly for all varieties used in the experiment under drought conditions. A lack of water limits the availability of NO_3^- by reducing its mobility in the soil plant system due to the decrease in denitrification and increase in mineralization (Saravia et al. 2016). This indicates that maximum fertiliser-use can be achieved with low N applications under well-watered conditions.

2.4.2.2 Nitrogen crop requirement

Rates and timing of N is dependent on different production regions and cultivars (Alva 2008). A study conducted by Westermann and Davis (1992) indicated that the cultivar Russet Burbank had N uptake rates of 2.4 to 4.0 kg ha^{-1} day^{-1}. In sandy soils, Lauer (1985) recommends N application rates of 340 kg ha^{-1}. Potato has a low N requirement during its early development from emergence to tuber initiation (Alva 2004). However, pre-planting N application is seen as important to maintain yield and stimulate tuber initiation

(Roberts et al. 1991; Rens et al. 2018). Zotarelli et al. (2014) reported that maximum daily N uptake occurred during the tuber bulking phase, which was 55 to 70 days after planting. The study showed that nitrogen applied at plant emergence and tuber initiation was more beneficial than application at planting. Application at these later stages ensured the availability of N in the soil between 30 and 80 days after planting, which coincides with the maximum daily N uptake. The application of 112 kg ha^{-1} and above at plant emergence was recommended and during the tuber initiation stage 56 kg ha^{-1} or below, as no significant benefit was seen in applying > 56 kg ha^{-1} at this stage. These findings are in agreement with da Silva et al. (2018), concluding that N application at emergence and tuber initiation are important in improving the NU_pE, but da Silva et al. (2018) emphasized the importance of N application at planting. Rens et al. (2016) reported that splitting N application between planting and tuber initiation to be a good management strategy to potentially reduce the N fertilisation requirement.

The decrease in NU_pE with increased fertiliser application is reported in the literature (Zebarth et al. 2004; Zotarelli et al. 2014; da Silva et al. 2018) for most cereal crops nitrogen uptake efficiency has been reported between 40 to 50% (Hallberg 1987). Applied fertiliser uptake efficiency has been reported in potato by various authors to be below 55%, depending on weather and N fertiliser management (Jiao et al. 2013; Rens et al. 2016). However, Westermann et al. (1988) reported higher N uptake efficiency at 60% and 80% for pre-plant and in-season applications, respectively. The low N uptake efficiency leads to higher N applications, particularly on coarse textured soils where N is known to be very mobile and leach easily. da Silva et al. (2018) reported findings of 18% fertiliser NU_pE for pre-plating applications, 44% at planting and 62% at tuber initiation. Zotarelli et al. (2014) concluded that N application at emergence and tuber initiation resulted in the highest N use efficiency, with values of 49 to 71% for an N rate of 100 kg ha^{-1}.

It is important for production managers to monitor the N status in plant tissue as well as soil N status (Vos 1999). This can be carried out extensively throughout the growing season by a petiole test and soil analysis. A study conducted on the effects of pre-plant and in-season N practices using petiole tests by Alva (2009) indicated that NO_3^- accumulated during the first 80 days after emergence within the shoots, is then translocated to the tubers in the subsequent period. It was also reported that at close to 100 DAP, the majority of the shoot and tuber nutrient accumulation was complete due to the low demand of N towards the end of the growing season. This stage can be referred to as the tuber-bulking phase. During this phase the roots' capacity to uptake nutrients is significantly reduced due to the decline in root growth. However, in a study conducted by Waterer (1997), the accumulation of NO_3^- took place up to 88 DAP and significantly influenced the yield obtained at the end of the growing season. Both the experiments concluded that petiole N concentrations are high in the early stages of the season and decrease towards the end of the growth period, with a sharp decline during the tuber bulking phase and that excessive N late in the season potentially retards tuber maturity (Waterer 1997; Alva 2009). Highest N demand is determined by variety and is a factor of the length of the growth season, root growth and distribution as well as the time taken to reach maturity. A study carried out by Iwama (2008) on the effect of genotype on root mass indicated that there was no significant relationship between cultivar and fertiliser rate on the potato crop, however, there was a large effect on root mass with an increase in fertiliser rate. The root mass was increased significantly.

2.4.2.3 Nitrogen leaching

Due to potato's effective root system being limited to the upper soil layers (Alva 2008), it results in a decreased NU_pE with particular effect on N. Soil characteristics, climatic factors and irrigation techniques and methods have an impact on the fate of nutrients. Sprinkler irrigation is often associated with high levels of leaching, where high water applications are correlated with large levels of N leaching (Alva 2004). Woli et al. (2016) reported that NO_3^- leaching was higher with longer irrigation intervals, larger irrigation amounts and higher N application rates. This was the result of more water being applied in longer irrigation intervals and larger amounts of water per irrigation event leading to deeper drainage. This effect was pronounced in production systems on sandier, lighter textured soils. However, the method of irrigation is not seen to have a significant effect on NU_pE (da Silva et al. 2018). Liao et al. (2016) concluded that even though yield was not affected, sprinkler irrigation caused higher soil N leaching from the top 20 cm of a sandy soil profile, compared to seepage irrigation. Even under well-managed irrigation scheduling and techniques there is still a risk of N leaching (Waddell et al. 2000).

2.4.2.4 Nitrogen management

The number of fertiliser applications during the growth season has been studied extensively. Vos (1999) conducted a study in the Netherlands on the effect of split N fertiliser regimes compared to single dose applications. The experiment indicated that up to 80% of the total N in the 'Russet Burbank' potato cultivar was absorbed between 20 and 60 days after sprout emergence. Saravia et al. (2016) reported that additional N applied 45 DAP was ineffective at inducing more tubers to initiate as the process at this time is nearing its end or at completion. A study carried out on the Chinese potato variety KX 13 by Sun et al. (2012), indicated that split dressing N was more efficient than applying the majority of the N source at once. This study concluded that N-application of 100 kg N ha^{-1} at planting followed by a top dressing of

50 kg N ha^{-1} one week before the tuber bulking stage, which was approximately 35 days after sprout emergence, accumulated the most DM. This high tuber DM yield can be associated with high transportation efficiency of assimilates from the above ground plant tissue to the tuber after tuberisation. The experiment also indicated that without N application at planting, N topdressing did not improve yields. If the initial rate of N supply is not adequate enough it results in the crop growth rate being affected, resulting in smaller leaves and a lack of vigour which in turn can influence and cause a depression in the rate of increase in the fraction of light interception. If N is available to the plant at high rates, there is a positive response on both vegetative growth and light interception (Oliveira 2000), thus, resulting in more photosynthetic assimilates being produced and transported to the tuber for growth (Vos 1999). Therefore, often farmers apply N at higher rates than the minimum requirement (Lemaire and Gastal 1997). The outcomes reported by Vos (1999) align with Sun et al. (2012), that splitting N fertiliser applications can lead to more efficient utilisation by the plant and no significant negative impacts on tuber DM yield were viewed. It can be concluded that tuber yield and quality are strongly affected by the rate and timing of N fertilisation (Munoz et al. 2005; Alva 2009; Woli 2016).

2.4.3 Phosphorus

2.4.3.1 Phosphorus source

Phosphorus (P) is considered critical in potato production systems and plays an important role in enhancing potato yield and quality. Potato tubers have a high P requirement and uses P inefficiently (Rosen et al. 2014). Phosphorus is considered the second most limiting nutrient in agricultural systems following N. Studies have shown its significant role in canopy development and LAI (Dyson and Watson 1971, Sale 1973, Jenkins and Ali 1999). A study conducted by Allison et al. (2001) on the effects of foliar versus soil applied P on potato concluded that foliar P had no effect on tuber yield or number and is not recommended for use in potato cropping systems. Chen et al. (2006) compared leaching losses of P from a rock phosphate and water-soluble source. The study reported that 96.6% of the water-soluble P applied had leached compared to 0.3 to 3.8% of the rock phosphate source and that this source is recommended on sandy soils.

2.4.3.2 Phosphorus crop requirement

Due to its lack of mobility and solubility in soils, P uptake and utilisation is often poor by crops. Irrigation management as well as soil drying and wetting cycles have been strongly linked to soil P availability (Suriyagoda et al. 2014). Phosphorus is associated with cellular energy, respiration and photosynthesis. The nutrient contributes to early development of the potato crop and is reported to increase the number of large tubers (Fernandes and Soratto 2016). A study conducted by Fernandes and Soratto (2016) on P uptake with regards to varying cultivars, indicated that varieties differ with regard to their response to P fertilisation. The variety Mondial produced a crop with higher tuber mass and had a higher available P use efficiency than the cultivar Agata. Mondial produced lower tuber numbers per plant and therefore, was able to allocate more carbohydrates to tuber growth, resulting in a larger mean tuber mass. These results agree with a study carried out by Fernandes et al. (2017) and conclude that DM accumulation is highest in the Mondial variety when compared to other commercially popular cultivars. Fernandes et al. (2017) showed that P fertilisation increased plant growth and tuber DM yield up to rates of 500, 250, 125 kg P_2O_5 ha^{-1} with regards to soils containing low, medium and high initially available P, respectively. Phosphorus use efficiency is especially notable in potato production systems, due to the shallow root systems often reported, resulting in limited P uptake. A study conducted by Sun et al. (2015) on the effects of various irrigation strategies (full irrigation, deficit irrigation, partial root zone drying) and P fertilisation on P use efficiency and WUE in potato production systems indicated that WUE increased significantly due to P application and not by irrigation regime. It was also concluded that P had a positive influence on leaf/tuber/plant total DM, leaf area, total plant P uptake and WUE. Negative effects were reported on the ratio of root:leaf area, stomata conductance, root P partitioning and P utilization efficiency. The high WUE can be attributed to the lower stomatal conductance when P fertiliser was applied. This resulted from a lower soil water content caused by a higher leaf area associated with P application on the crop's canopy. This was in agreement with a study conducted by Motalebifard et al. (2013), which concluded that P significantly influenced WUE, ET, tuber numbers and tuber yield of a potato crop. In contrast, another study conducted in the United States of America by He et al. (2011) showed that irrigation influenced stable and recalcitrant P fractions within the soil by redistributing and mobilising P. A difference of 91 mg P kg^{-1} within the field studies suggests that three-year consecutive irrigation lowers the top 20 cm of the soil P by an average of 5.4%.

2.4.3.3 Phosphorus leaching

Research on P losses via the process of leaching has received very little attention compared to losses occurring from erosion and run-off (Fortune et al. 2005). Fortune et al. (2005) concluded that P losses through leaching are environmentally significant and contribute towards the detrimental effects of eutrophication, which initiates at 20 to 30 µg P L^{-1}. However, the leaching losses (kg P ha^{-1}) are insignificant in economic terms for producers, so very little attention is paid to P leaching. Movement of P in soils is influenced by the rate at which P is applied and the reaction of P within the soil (Reddy et al. 1980). Atalay (2001) concluded that soil particle size and soil type related to P sorption in profiles and that the presence of organic matter played a large role in P sorption in Entisol soil profiles.

2.4.3.4 Phosphorus management

Soil testing is generally the most common method for determining the crop P requirement and additions needed. There are various methods used: the Olsen sodium bicarbonate extraction method is more commonly used on alkaline soils, whereas the Bray I or Mehlich I or III are used on more acidic soils (Maier et al. 1989). Various placement and timing methods of P fertilisation have been suggested and recommended. The general methods include pre-plant broadcasting or broadcasting within the season, band placement near the seed during planting or as a liquid source during crop growth. A study conducted by Hawkins (1954) showed that banding applications of P resulted in better growth response when compared to broadcasting applications. This was confirmed by Sparrow et al. (1992) and Kelling and Speth (1997).

The effect of P on tuber specific gravity (SG) has been reported to vary according to the soil test P levels. If soil P levels are low, additional P application increases SG (Rosen et al. 2014). This coincides with studies by Roberts et al. (1984) and Sanderson et al. (2002). If soil P levels are high, then additional P has very little effect on tuber SG (Laboski and Kelling 2007). A decrease in tuber SG with high rates of P application has also been observed (Freeman et al. 1998). The potato crop generally takes up greater proportions of P later on in the season, compared to N and K (Roberts et al. 1991). Its absorbance of P is most rapid from 40 to 60 days after emergence (Kelling et al. 1998). However, in-season application of P with irrigation water is successful when potato roots are shallow and close to the soil surface (Rosen et al. 2014). Soils vary largely in terms of P content and availability. The type of clay, organic matter and soil chemistry determines the availability of P, also known as labile P. Phosphorus rate factor and the cultivar used determines uptake of other nutrients. Soils low in P availability have been viewed to result in the uptake of 3 to 4 times more N, K, Ca, Mg and S when P fertilisation has taken place up to a rate of 500 kg P_2O_5 ha^{-1} (Fernandes et al. 2017). Thus, the application of P implicates the absorption of other mineral ions as well as its own.

2.4.4 Potassium

2.4.4.1 Potassium source

The most common sources of potassium (K) are K–chloride, K–sulphate and K–nitrate. Various research concludes that differing K–sources have an effect on yield as well as SG. Potassium chloride has a negative influence on SG, however, Toolangi (1995) reported that the reduced SG is mainly caused by the chloride ion. A study conducted by Davenport and Bentley (2001) did not detect any influence of K–source on tuber SG. In contradiction to this Kumar et al. (2007), who studied nine various K–sources and their effects on tuber yield and quality parameters, observed an increase in both yield and tuber SG when the sources K–sulphate and K–nitrate was used in comparison to K–chloride. This study concluded that for the growth of processing tubers, the source K–sulphate should be the preferred over K–chloride. The sulphate form results in a higher DM percentage, therefore, increasing the crisp yield and reducing oil content percentage. Similar findings were reported by Yakimenko and Naumova (2018). However, both studies concluded that the influence of K–source on SG and tuber yield are cultivar-dependent.

2.4.4.2 Potassium crop requirement

Potassium is a nutrient that is taken up in the greatest quantity in potato production systems (Ati et al. 2012). Various studies agree that it has a great effect on both tuber yield and quality (Hannan et al. 2011; Ati et al. 2012; Khan et al. 2012). According to Khan et al. (2012) and Hannan et al. (2011), quality parameters such as DM content, starch concentrations, vitamin C contents as well as colour and taste are largely affected. The optimum application rate of K in potato cropping depends on soil characteristics. Rates recommended vary slightly in the literature. A study conducted by Hannan et al. (2011) reported tuber yield to plateau at 150 kg K ha^{-1} with the greatest yield at 182 kg K ha^{-1}. These results correspond to Khan et al. (2012), who stated that 150 kg K ha^{-1} satisfied potato plant K requirements when using murate and sulphate sources. A study carried out on WUE under different irrigation methods and K applications by Ati et al. (2012), however, recommends that in order to achieve the highest yields, 600 kg K_2SO_4 ha^{-1} (270 kg K ha^{-1}) can be applied when using drip or furrow irrigation systems. However, high application of K can reduce DM contents and there is an inverse relationship between K and reducing sugars (Hannan et al. 2011). The plant growth stage when maximum tuber K accumulation occurs is between 30 and 60 days after planting. Tubers at this stage are able to accumulate up to 78% of the total required K (Hannan et al. 2011). The rate of K application also influences the number of tubers that form. Low and excessively high rates of K significantly reduce the number of tubers (Kavvadias et al. 2012). Trehan and

Sharma (2002) reported the need of K early on in potato crop growth in order to promote early root production, however, root uptake efficiency of K by potato varies considerably between cultivars and is affected by the root:shoot DM accumulation (Trehan and Claassen 1998). An optimum K uptake efficiency was reported by Trehan and Claassen (2000) and was determined by time, as there was an increase in K-influx with an increase in time. The same study concluded that shoot and root growth was dependent on K availability at the early growth stages and the growth ratio was higher at higher K levels. A shoot K content of 4 to 5% is adequate to produce 90% of maximum shoot growth rate, which is achieved quicker if soil solution K is optimum early on, compared to plants grown at low K concentrations. These conclusions were agreed upon by Trehan et al. 2005.

2.4.4.3 Potassium leaching

Potassium is a mobile ion and therefore, leaching of significant amounts may occur in cropping systems. The leaching of K is dependent on various soil factors such as organic matter content, clay percentage and the concentration of other cations present within the soil solution (Kolahchi and Jalali 2006; Jalali and Rowell 2009). Potassium leaching is specifically notable in coarse textured soils such as those commonly used in potato production systems. A study by Spiers and Besson (1992) reported the significance of K leaching on sandy soils. It is also noted that the presence of accompanying anions influences the rate at which K is leached. Sharma and Sharma (2013) concluded that K leaching in the presence of other anions follows the order of $SO_4^{2-} < H_2PO_4^{2-} < NO_3^- = Cl^-$. This effect has also been described by Hingston et al (1972) and Sposito et al. (1983). Also presented was higher losses in K through leaching as observed when the application of K was high followed by regular irrigation or rainfall events.

2.4.4.4 Potassium management

It is a common practice to apply the entire quantity of K at the time of planting as a basal dressing. Davenport and Bentley (2001) and Kumar et al. (2007) reported no significant benefit in the split application of K. Gunadi (2016) indicated a positive response of tuber yield to the split application of K fertilisers between planting and six weeks after planting. In sandy soils the reduction of K application at planting by split application, can reduce the increased potential of leaching (Sitthaphanit et al. 2009). Methods of determining K requirement are described by Li et al. (2015) and include soil testing, agronomic efficiency and K balance in the plant-soil system. The study showed a negative K balance, which concurs that mining of K is occurring as more K is moving out of the system than is being applied through fertiliser.

2.4.5 Calcium

The importance of Calcium (Ca) in plant physiology is described in the literature (Burstrom 1968; Palta 1996; Palta 2010). The tuber bulking stage is seen as important with regards to the application of Ca fertilisers, with the largest effect on tuber Ca concentrations occurring at this physiological stage (Gunter et al. 2000). However, Ca application during the early stages of tuber development have been shown to reduce the incidence of internal brown spot (Olsen et al. 1996). If calcium is withheld during tuber initiation, negative symptoms can occur (Davies 1998).

Different forms of Ca fertilisers are available. Water-soluble forms include Ca–nitrate and Ca–chloride, which usually come blended with urea or urea ammonium nitrate (Ozgen et al. 2006). Ozgen et al. (2006) studied the effects of various sources of Ca (Ca–nitrate and Ca–chloride) and their combined effects with or without gypsum on tuber Ca concentrations and internal brown spot. Results concluded that soluble Ca application without gypsum increases tuber Ca concentrations and reduced internal brown spot. This was agreed upon by Karlsson and Palta (2002). Results regarding this topic are, however, controversial as a study by Simmons et al. (1988) indicated that gypsum increased tuber Ca concentrations. Another study by Simmons and Kelling (1987) found gypsum and Ca–nitrate to be more effective than gypsum alone. A study on the effect of calcitic lime in potato production indicated that liming either reduced or did not affect yield or tuber number (Maier et al. 2002). Studies of liming in potato production systems have reported contradictory results (Sparrow and Salardini 1997). However, the benefits of practices to increase soil pH in slightly acidic Entisol soils under potato production by 0.6 to 3.1 (pH_{water}) have been reported by Maier et al. (2002). Calcium fertiliser timing, rates and placement play a vital role in the increase in tuber Ca concentrations (Kratzke and Palta 1986). The presence of functional roots on the tuber and tuber-stolon junction means that in order to increase tuber Ca concentrations, Ca placement must be close to the tuber as is indicated by Kratzke and Palta (1986). The sandy soils on which potato production often occurs are typically low in Ca due to constant irrigation and the depletion of soluble Ca in the profile, therefore, it is important to supplement soluble Ca in sandy soils as tuber Ca deficiencies are common (Kleinhenz et al. 1999).

2.4.6 Magnesium

The importance of Magnesium (Mg) and its physiological effects on plants is reported in the literature (Cakmak and Kirkby 2007). However, it is often considered the “forgotten nutrient” (Cakmak and Yazici 2010). Orlovius and McHoul (2015) described a clear increase in leaf Mg concentrations with the application of Mg fertilisers. The study compared the mean increase in leaf Mg concentrations between Kierserite and calcined magnesite. It was concluded that kierserite performed better due to a higher solubility of Mg. Mikkelsen (2011) reported significant variability of Mg fertilisers with regards to their water solubility. The solubility of Mg is an important factor to consider regarding sustainable agricultural systems (Gransee and Führs 2013). The effects of these differing water solubilities are described by Sher (2002). More soluble Mg sources include Epsom salts (Mg–sulphate), serp-super A and serp-super B (Hanly et al. 2005). Fertiliser type and soil properties are factors affecting the effectiveness of Mg sources (Hanly et al. 2005). Mondy and Ponnampalam (1986) compared the effect of Epsom salts and Dolomite on potato tuber quality. The results show that Epsom salts produced higher nitrogen within the potatoes whereas tubers receiving dolomite were significantly higher in manganese and cadmium contents. Both sources of fertilisers increased Fe and Al concentrations within the tubers. Fertiliser regimes of Mg vary widely between regions and countries (Ristimäki 2007). Grzebisz (2013) stated that Mg fertilisation should focus on its effect on N management as it plays a role in the plant’s ability to access and utilize N. However, Allison et al. (2001) reported no significant effect on potato production There is large competition involved between various cations, particularly notable is the antagonism between Ca and Mg (Gericke 2018). Gericke (2018) indicated the higher affinity of potato roots to absorb Ca^{2+} ions than hydrated Mg^{2+} ions. However, increasing the Mg content in the tuber was easier than increasing the Ca content due to the higher mobility of Mg in the plants.

2.4.7 Sulphur

A shortage of Sulphur (S) has a negative effect on sugars, asparagine and other amino acids in potato (Elmore et al. 2010). However, Barczak and Nowak (2015) indicated the potato crop’s low requirement for S. The study concluded that irrespective of the fertiliser source and rate, sulphur application did increase the tuber’s N, S and Mg concentrations whilst decreasing Ca tuber content. Sulphur is usually applied as sulphate through sources such as Mg–sulphate, zinc–sulphate, K–sulphate, gypsum and others (Alva et al. 2008; Barczak and Nowak 2015). Sulphur is leached as sulphate and dissolved organic S and is potentially one of the more important factors affecting S depletion (Zhao and McGrath 1994). A study by Eriksen (2009) using lysimeters reported values of sulphate leaching of 1 to 60 kg S ha^{-1} y^{-1}. Up to 100 kg S ha^{-1} y^{-1} leaching has been reported by Guzys and Aksomaitiene (2005). Alva et al. (2008) concluded that the application of gypsum caused increased levels of Ca and sulphate in leachate in fine sand. The high loading of Ca results in the displacement and leaching of other cations such as Mg.

2.5 Synopsis

With water becoming increasingly scarce, methods to improve irrigation efficiency are becoming imperative (Greenwood et al. 2010). Irrigation scheduling and practices can potentially optimise WUE, along with enhancing the economic and environmental sustainability of irrigated agriculture (Levidow et al. 2014). Water use is only effective when best management practices are combined alongside technology (Levidow et al. 2014). However, if used poorly, irrigation technology can cause unnecessary losses affecting overall sustainability and water productivity. The difficulty is to get farmers to view WUE as saving water instead of the perception of solely maximising net revenue (Knox et al. 2012). Most irrigation scheduling is carried out on the bases of farmers past experience and subjective judgements and is often controlled by the availability and cost of water to farmers (Greenwood et al. 2010, Knox et al. 2012).

This literature review has indicated a lack of knowledge with regards to irrigation and fertilisation management in potato production systems in sandy textured soils. Little is known about the movement of fertiliser and water past the effective rooting depth and the losses that are occurring from these production systems. The following study will touch on the inputs and losses in potato production systems in the Sandveld region of the Western Cape in order to optimise and recommend better management practices, to avoid unnecessary waste and the negative environmental impacts that may be occurring. Water availability to potato crops is thus, essential for controlling productivity with importance to arid and semi-arid climates and plays an important role in the nutrient uptake from the soil profile and fertiliser applications. The potato crop has a very sensitive response to water deficits and its shallow root zone impact on the water and nutrient use efficiency (Shock et al. 2007; Monneveux et al. 2013; Monneveux et al. 2014). Therefore, special emphasis is on the adoption of practices to improve water and nutrient use efficiencies (Badr et al. 2012). This ensures the need for extensive research on the sustainability of irrigation in these climatic areas to optimise irrigation and nutrient management strategies.

CHAPTER 3: MATERIALS AND METHODS

3.1 Locality and experimental design

A field study was conducted in the Sandveld region along the West Coast of the Western Cape Province (Figure 3.1). Nine fields, which were evenly distributed throughout the region, were selected for monitoring. The area typically constitutes a Mediterranean-type climate with cool, humid winters and hot, dry summers (Figure 3.2). The wind blowing from the cold Atlantic ocean inland keeps temperatures cool enough in the summer for potato production and prevents frost in the winter months (Haverkort et al. 2013). Although potatoes can be planted all year round, there are two main crop-planting seasons per year, namely the autumn (March to April) and winter (July to August) planting periods. Due to low and sporadic rainfall, irrigation using mainly borehole water is required to ensure an adequate supply of water to achieve economically feasible potato yields (Archer et al. 2009). Potato production is conducted with the use of centre-pivot irrigation systems.

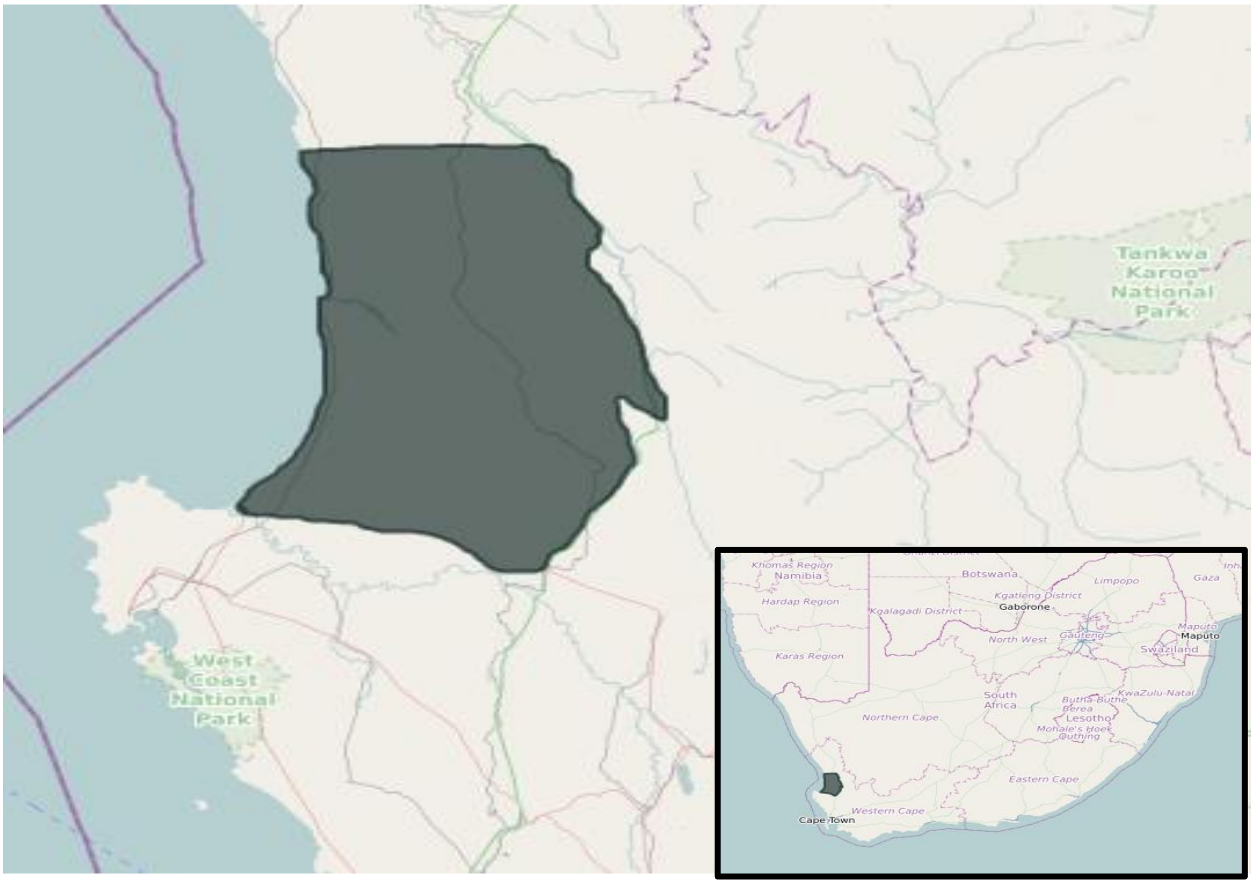

Figure 3.1. The shaded area indicates the borders of the Sandveld region in South Africa. Selected studied fields were located within this area.

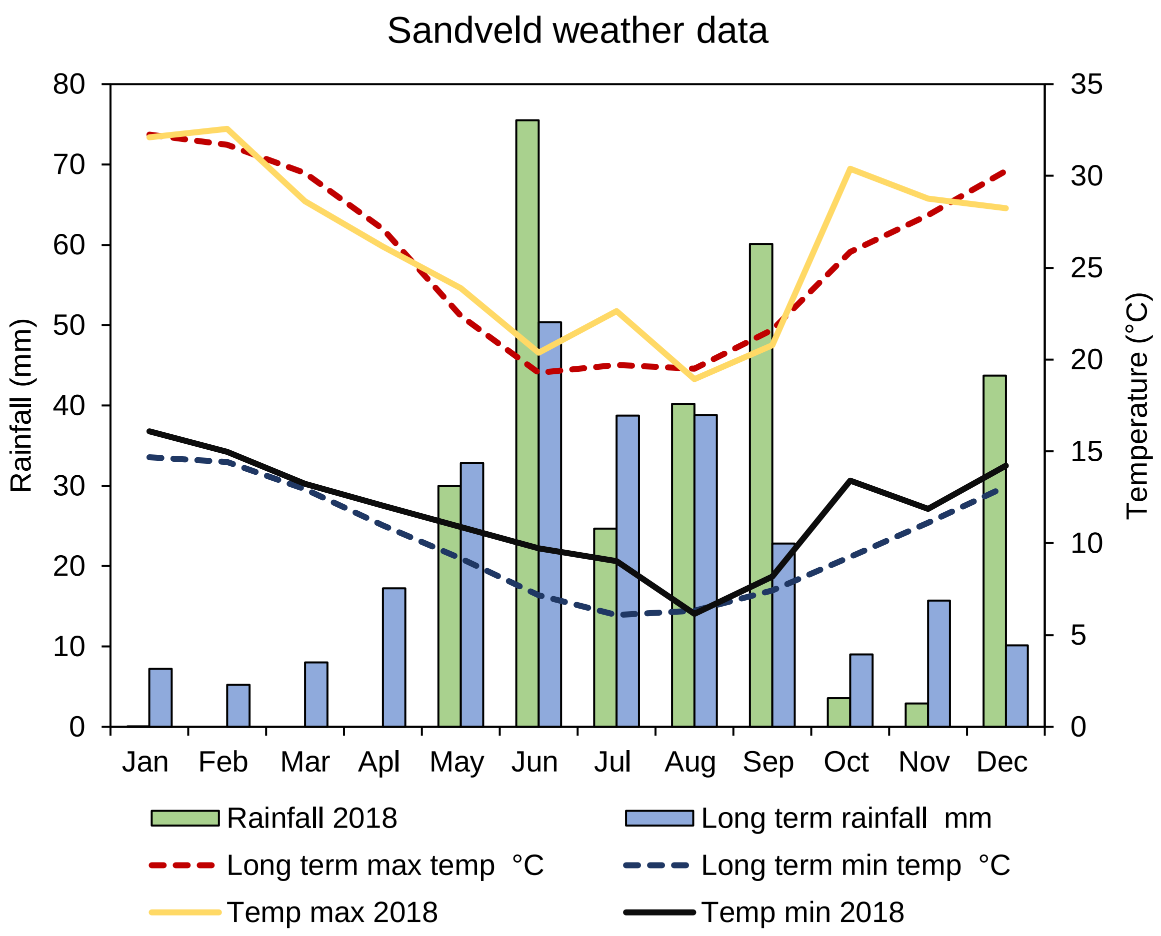

Figure 3.2. Accumulated monthly precipitation and average minimum and maximum temperatures for 2018 in the Sandveld region, compared with the thirteen-year average (2005 – 2018). Source: Agricultural Research Council.

Field work commenced in March 2018 and was conducted over a period of one year, terminating in March 2019. Commercial potato producers were selected, in order to give an indication of large-scale production practices within the region. Selection was based on a survey conducted by Steyn et al. (2016), which identified high and low resource using farmers in the region. A combination of both high and low resource use producers was then selected and the cultivars FL2108 or Sifra was grown in the studied fields. Six fields were intensively monitored, while a further three fields were extensively monitored (Table 3.1). The study spanned over a period of two seasons, namely autumn/winter (March-August 2018) and summer (October-November 2018) planted crops. Planting dates varied throughout the year and was eclectic between farmers, giving a wider range of growth conditions during cropping cycles. Production practices were not prescribed to the producers and only current farming practices carried out in the area were monitored.

3.2 Data collection

Each field was fractionated into four equal quarters and each segment was given a compass heading (i.e. NE, NW, SE, SW). The differences in equipment installation between the intensively and extensively monitored fields is illustrated by **Error! Reference source not found.**. Equipment used to monitor water input through rainfall and irrigation, drainage and leaching past the root zone and soil water content within each field was installed during the same date. Installation took place two to three weeks after the field was planted (Table 3.1), preferably just before or directly after crop emergence. Fields were visited fortnightly for data collection and soil solution sampled during those visits (intensive fields).

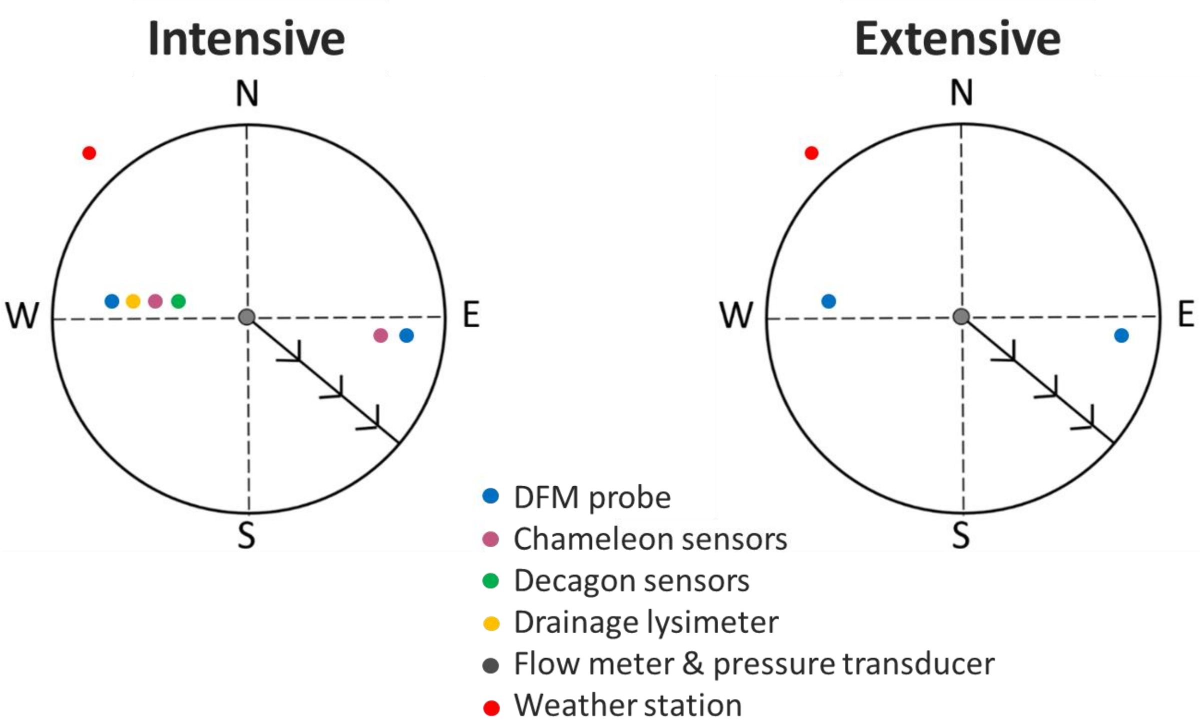

Figure 3.3. Distribution of equipment used to measure water and nutrient inputs and losses in selected potato fields under centre-pivot irrigation. Intensively monitored (left) and extensively monitored (right) fields varied with regards to equipment used.

Table 3.1. Information regarding locality, equipment installation, planting date, emergence and harvest date of the studied fields. Fields 1 to 9 are labelled according to their planting dates (1 = earliest planted and 9 = last planted).

Type	Field	Location	Altitude (masl)	Installation date	Planting date	Emergence	Harvest date
Intensive	*Field 2	32°36'53.85"S 18°27'43.97"E	219	24-Apr-18	28-Mar-18	10-Apr-18	16-Aug-18
	Field 3	32°36'40"S 18°27'30"E	133	22-May-18	02-May-18	04-Jun-18	23-Oct-18
	*Field 5	32°22'0.19"S 18°41'57.7"E	219	22-Aug-18	27-Jun-18	30-Jul-18	15-Nov-18
	Field 7	32°50'45.3"S 18°33'03.3"E	47	07-Aug-18	31-Jul-18	21-Aug-18	27-Nov-18
	*Field 8	32°38'5.46"S 18°28'33.67"E	115	23-Oct-18	11-Oct-18	01-Nov-18	07-Feb-19
	Field 9	32°25'20.74"S 18°20'21.87"E	8	04-Dec-18	30-Nov-18	06-Dec-18	27-Mar-19
Extensive	Field 1	32°41'1.88"S 18°42'18.15"E	92	14-Mar-18	03-Mar-18	29-Mar-18	20-Jul-18
	Field 4	32°37'23.5"S 18°27'27.0"E	123	10-Jul-18	25-Jun-18	21-Jul-18	13-Nov-18
	Field 6	32°37'31.3"S 18°37'22.2"E	110	06-Aug-18	09-Jul-18	06-Aug-18	13-Nov-18

*Fields where equipment was installed after plant emergence. The water flow meter for Field 7 was installed earlier than the other equipment on the 10th of July 2018. For Field 8 the water flow meter was installed after all the other equipment, on the 6th November 2018.

3.3 Irrigation system evaluations

Irrigation system performance tests were conducted on all centre-pivots during the early stages of crop growth (Koegelenberg and Breedt 2003; Griffiths 2006). Detailed evaluations were carried out to assess centre-pivots with regards to nozzle packages, working pressure, application efficiency and distribution uniformity. Working pressure at the centre and end of the system was measured using calibrated manual pressure gauges. Manual rain gauges were packed out at 5 m intervals along the length of the system (excluding the first 20% of the pivot, as recommended by Koegelenberg and Breedt (2003)). The system was then placed on a 25 to 30% speed setting or pre-set irrigation amount (e.g. 10 mm) and run over the rain gauges. The volume of water collected by each rain gauge was then recorded and the different uniformity and efficiency parameters assessed. Application efficiency (AE) indicates the portion of water applied by the sprinklers that reached the soil surface and thereby determines the wind drift and evaporation losses that occurred (Equations 3.1 and 3.2). The uniformity coefficient of Heerman and Hein (CU_{HH}) gives an indication of how evenly the distribution of applied water is within the irrigated area and was calculated using the Heerman and Hein (1968) modified equation (Equations 3.3 and 3.4). The distribution uniformity of the lower quarter (DU_{lq}) compares the average of the lowest 25% of measurements with the average value of all other measurements to determine if significant under irrigation is occurring on a specific area (Equation 3.5). The maximum rate at which water was being applied at the outer end of the pivot was also measured, using a tipping bucket rain gauge and datalogger or a manual rain gauge and stopwatch. This gives an indication of the runoff risk for the specific soil and irrigation system combination.

$$\mathrm{AE} = 100\left[\frac{N_A}{G_A}\right] \tag{3.1}$$

$$G_A = \frac{F_r}{(A \times 10) \times R_s} \tag{3.2}$$

$$CU_{HH} = 100\left[1 - \frac{\sum_{i=1}^{n} S_i\left|V_i - V_p\right|}{\sum_{i=1}^{n} V_i S_i}\right] \tag{3.3}$$

$$V_p = \frac{\sum_{i=1}^{n} V_i S_i}{\sum_{i=1}^{n} S_i} \tag{3.4}$$

$$DU_{lq} = 100\left[\frac{Q_l}{N_A}\right] \tag{3.5}$$

where:

N_A indicates the net application (mm) of water by the centre-pivot

G_A is the average gross application (mm) as calculated by Equation (10)

F_r is the water flow rate in $m^3\ h^{-1}$

A is the field area (ha)

R_s is the systems rotation time at a specific speed setting (h) n is the number of rain gauges used in the evaluation

i is the number used to tag a particular rain gauge with i = 1 being closest to the centre of the pivot and i = n for the outermost rain gauge from the centre

S_i refers to the distance of the n^{th} rain gauge from the pivot centre

V_i is the volume of water collected in each rain gain (i^{th})

V_p is the weighted average of the volume of water collected

Q_l is the average of the lowest 25% readings taken from the rain gauges.

The speed of the pivot was measured by timing the periods that the wheels moved and remained stationary. This was conducted on the outermost set of wheels as they travel fastest to cover the further distance. The test was carried out at a 25 to 30% speed setting on the pivot. Each time the wheels halted; a peg was placed into the soil in-line with the centre of the wheel hub. This was replicated a total of four times and the distance between each peg measured.

The flow rate of water through the system was measured using the installed electromagnetic flow meter. As a check, a clamp-on ultrasonic water flow meter was used to measure the accuracy of the flow meter readings. The flow rate readings were then compared to actual application volumes collected by the packed-out rain gauges.

3.4 Irrigation amount

Irrigation amounts were continuously logged by electromagnetic flow meters and pressure transducers with dataloggers (Equations 3.6 and 3.7)[1]. These were installed on all centre-pivot irrigation systems. The flow meters and pressure transducers allowed the monitoring of irrigation times, pressures and volumes, as well as a check to assess the accuracy of the equipment against each other. The pressure transducers were located at the centre of the pivot where the water entered the main pipe leading to the boom. Readings taken by the pressure transducer loggers were manually downloaded every fortnight during site visits. The flow meters were installed on the main pipeline leading into the pivot system. The flow meters were able to measure when the irrigation system was turned on and off and log the duration the system was on at each irrigation cycle, as well as measure the volume of water flowing through it to give accurate readings of irrigation volumes. The readings were then transmitted by GPRS telemetry. An assumption was made that the flow meter readings were more accurate than the pressure transducers readings.

[1] Running time was calculated on a pressure of > 40 kPa. (1L m^{-2} = 1 mm)

$$EFM = \frac{F_t}{(A \times 10\ 000)} \tag{3.6}$$

$$PT = \frac{R_t \times [F_r \times 1000]}{(A \times 10\ 000)} \tag{3.7}$$

where:

EFM refers to the water application (mm) measured by the electromagnetic flow meter;

PT is the water application (mm) measured by the pressure transducer;

F_t is the total flow indicated by the electromagnetic flow meter (in litres);

R_t is the running time of the centre-pivot (h).

A refers to the area under the centre-pivot boom (ha)

Fr is the water flow rate in m^3 h^{-1}.

Water samples used for irrigation of each field were collected from the water sources. The samples were kept at 4°C along with the soil solution samples and later sent to a lab for nutrient analysis. Application of nutrients (I_N, kg m^{-3}) to each field due to the presence of elements within irrigation water (N_w) was determined at the end of the season (Equation 3.8), using the total amount of water applied (W_T) in m^3 per hectare.

$$I_N = N_w \times W_T \tag{3.8}$$

3.5 Leaching requirement

The leaching requirement (LR) was calculated for each intensively monitored field. For the irrigation water a threshold electrical conductivity (EC) value of 170 mS m^{-1} was used as the maximum permissible conductivity allowed without major yield reduction (Fertasa 2016). The leaching requirement (Equation 3.9) allowed for a yield reduction of 10% was then calculated.

$$LR = \frac{EC_{iw}}{(5EC_s - EC_{iw})} \tag{3.9}$$

where:

EC_{iw} refers to the electrical conductivity of the water source used for irrigation;

EC_S is the level of soil salinity level is allowed to occur, resulting in a 10% yield reduction (250 mS m^{-1}) in potato production (Fertasa 2016).

In order to calculate the total water requirement (TWR), including the irrigation water needed to leach out excess salts, the gross water requirement (GWR) (water requirement taking into account losses occurring during application) must be multiplied by the LR as indicated in Equation 3.10.

$$TWR = (GWR \times LR) + GWR \tag{3.10}$$

At the end of crop growth WUE and IWUE or IWP (kg mm^{-1}) was calculated using fresh tuber yield (T_y) in kg ha^{-1} and total irrigation and rainfall amounts for the season (mm) (Equations 3.11 and 3.12). It refers to the kg of fresh tubers produced per mm of water applied through irrigation or irrigation plus rainfall.

$$WUE = \frac{T_y}{irrigation + rainfall} \tag{3.11}$$

$$IWUE = \frac{T_y}{irrigation} \tag{3.12}$$

3.6 Crop evapotranspiration

Crop evapotranspiration (ET) was calculated using the FAO-56 basal crop coefficient (Kcb) curve method (Allen et al. 1998) A graphical curve was produced for each field, using measurements made during the season. A basal crop coefficient [Kcb(ini)] of 0.15 was used from date of planting to date of crop emergence. The values of the basal crop coefficient at full (100%) canopy cover [Kcb(mid)] to the end of full canopy cover and end of full canopy cover to senescence [Kcb(end)] were adjusted $Kcb_{(adj.)}$ for climatic conditions using Equation 3.13.

$$kcb_{(adj.)} = kcb_{(table)} + [0.04(U_2 - 2)] - 0.004(RH_{min} - 45)\left(\frac{h_{max}}{3}\right)^{0.3} \tag{3.13}$$

where:

$Kcb_{(table)}$ refers to the FAO-56 values for Kcb(mid) (1.10) and Kcb(end) (0.65) (Allen et al. 1998);

RH_{min} is the average of the minimum relative humidity calculated during the period of full canopy cover [Kcb(mid)] or decrease in growth from full canopy cover to senescence [Kcb(end)];
U_2 refers to the average wind speed at a 2 m height during the different periods;
h_{max} is the maximum plant height reached at full growth, which was taken as 0.6 m (Allen et al. 1998).

The determination of 100% canopy cover was taken as 650-degree days from crop emergence (Haverkort et al. 2015). Full canopy cover was ended at 100 DAP. Basal crop factor for the end of growth [Kcb(end)] was taken as 120 DAP and if crop growth exceeded 120 days, then Kcb(ini) was assumed at 140 DAP, whereafter if irrigation proceeded then the crop coefficient remained Kcb(ini). However, if irrigation seized from 140 DAP, ET was terminated. The Kcb values between these points were then calculated using linear-regression to produce a full season curve. An example of the curves produced is illustrated in Figure 3.4.

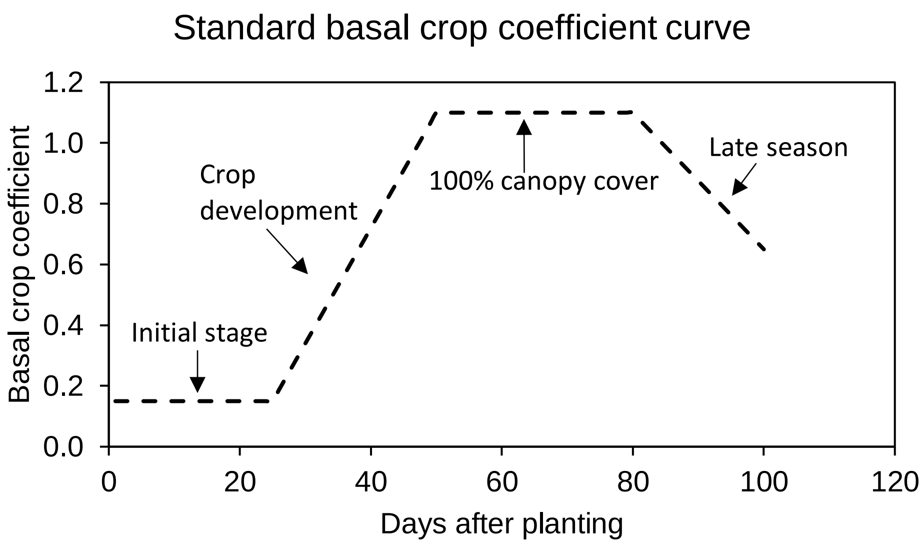

Figure 3.4. Example of a basal crop coefficient curve from FAO-56 (Allen et al. 1998)

The LINTUL DSS potato model (Haverkort et al. 2015) was also used to estimate ET requirements for each crop using various factors such as climatic and soil properties as input parameters.

From the simulated ET (mm) requirement from the Kcb curves and LINTUL DSS model, irrigation requirements (mm) (IR) was calculated, using each centre-pivot's AE (Equation 3.14).

$$IR = \frac{ET}{(AE \div 100)} \tag{3.14}$$

3.7 Soil water content and water movement in the soil

Soil water content and water movement through the profile were monitored using Decagon soil capacitance probes, DFM (Dirk Friedhelm Mercker) multifunctional soil capacitance probes (with telemetry) and Chameleon sensors. The intensively monitored fields contained all three types of probes and the extensive fields contained only DFM probes. The reason for the use of a wide variety of soil probes was to compare the accuracy of each probe in these sandy soils to recommend the most suitable to use in those conditions in addition to viewing water movement throughout the soil profile. Data from the Decagon logger was downloaded every fortnight. The DFM probes were linked to the network and continuously sent data to a local website. Chameleon data was not continuously logged, but instantaneous readings were taken by farmers and the data logged was downloaded to the network every two weeks, during site visits.

One set of Decagon capacitance probes, consisting of five sensors, was installed in each intensively monitored field (Figure 3.5). The sensors were installed at depths of 10, 20, 30, 40 and 50 cm on the ridge (Figure 3.5). The probes were connected to a Campbell CR200 datalogger and measured change in dielectric constant of the soil, which is altered by the volumetric water content of the soil.

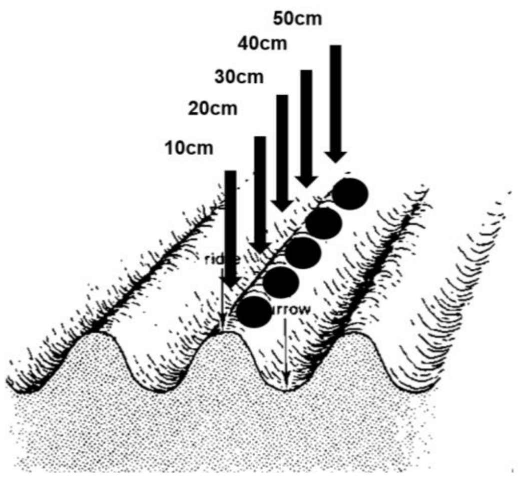

Figure 3.5. Placement of Decagon soil capacitance probes along a planting ridge and the depth at which each sensor is located. Temperature was measured along with the sensor placed at a depth of 10 cm.

A 12 V battery was used to power the data-logger. The battery voltage was checked at every site visit and when voltage dropped below 12.5 V, the battery was swapped. For Fields 8 and

9 gravimetric soil water content (ω) was measured by removing soil near the Decagon probes at the depth of each sensor, 0 to 10, 10 to 20, 20 to 30, 30 to 40 and 40 to 50 cm. The time of soil removal was recorded to compare the results with the logger readings in order to gauge the accuracy of the DFM and Decagon probes. The removed soil was placed in brown paper bags, which were then inserted into a plastic bag and sealed. Samples were weighed in the lab in the paper bag and plastic bag. The plastic bag was then removed and the paper bag along with the soil placed in an oven at 108 °C for five days. Once dried, the samples were removed, weighed and the ω was determined using Equation 3.15. The Decagon and DFM probes measure volumetric soil water content. Therefore, the gravimetric water contents determined were multiplied with the bulk density of the soils as determined by soil analysis in order to obtain volumetric soil water content.

Empty paper bags and plastic bags of the same size and dimensions used for sampling were weighed and the weights noted. Empty paper bags were also placed in the oven at 108 °C for the same duration as the soil samples to obtain a dried mass. The weights were then deducted during the calculations in order to get the weight of the soil alone.

$$\omega = \frac{S_W - S_D}{S_D} \tag{3.15}$$

where:

ω refers to gravimetric water content (kg kg^{-1} or g g^{-1});
S_W refers to the wet soil mass (kg);
S_D is the soil mass after drying (kg).

Chameleon sensors were placed at 15, 30, 50 cm depths from the top of the planting ridge. Two sets of Chameleon sensors were placed in each field, alongside the DFM probes (refer to **Error! Reference source not found.**) Unlike the Decagon probes, these sensors w ere placed at different depths in the same augured whole within the row as illustrated in Figure 3.6. The sensor is coated with gypsum, which allows soil water to move through the coating whilst creating a constant EC (Stirzaker et al. 2014). Located in the centre of the gypsum coating is two gold-plated electrodes that measure resistance across a medium, mimicking the suction required by plant roots in order to absorb water from the soil. Due to the fact that the sensors measure soil tension (water potential, not water content), they do not require calibration for differing soil types. The sensors, however, differ from that of a gypsum block as they do not measure the resistance across the gypsum. Loggers for the gypsum sensors were given to farmers who were instructed to take three readings per week.

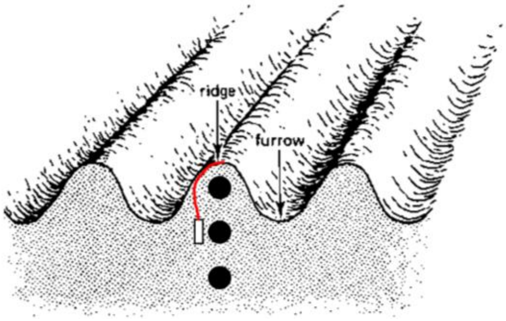

Figure 3.6. Placement of Chameleon logger sensors at depths of 15, 30 and 50 cm. When connected to the sensors the logger reads three sensors and displays a colour (LED light) for each sensor depth; red, green and blue, depending on the measured resistance. The three colours represent a tension of >50 kPa, 20–50 kPa and 0–20 kPa, respectively (Stirzaker et al. 2017). A tension of 0 kPa indicates a soil that is saturated and > 50 kPa represent a dry soil.

Two DFM probes were installed per field, on all fields. The probes were installed on opposite sides of the pivot road (refer to **Error! Reference source not found.**) and logged data from a depth of 10 to 60 cm at 10 cm increments. At each depth, the probes also logged temperature readings (DFM Software Solutions 2015).

3.8 Drainage

Drainage and leaching were measured through the use of drainage lysimeters, which were installed in intensively monitored fields and located 3 to 10 m from the centre road of the centre-pivot field. Lysimeters were located along the second- or third-wheel track from the centre of the pivot (depending on field size), but 3 to 5 m to the side of the track (Figure 3.7).

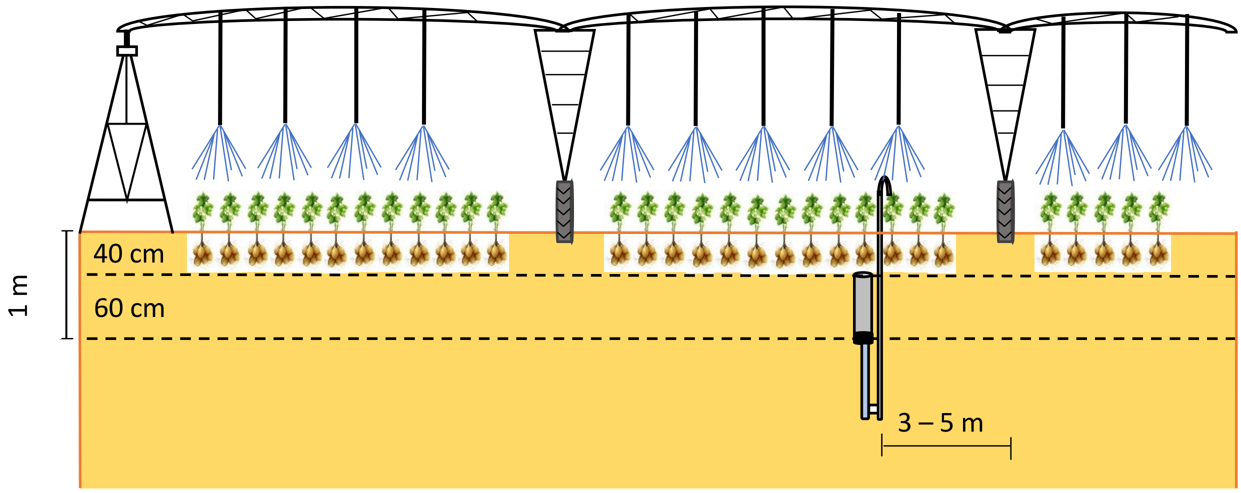

Figure 3.7. The positioning of the drainage lysimeter within the soil profile, including the depth and distance from the pivot track. The drainage lysimeter was installed either side of the second- or third-wheel track.

The type of drainage lysimeter selected was a passive capillary lysimeter, which consists of two main components (Figure 3.8): a divergence control tube (DCT) and a fibreglass wick. The function of the fibreglass wick was to create a hanging water column to mimic the tension of the surrounding soil, preventing an effect commonly occurring in other types of lysimeters known as the boundary layer effect due to water ponding at the bottom of the lysimeter. Therefore, due to the fibreglass wick this form of lysimeter has an increased efficiency of water capture and improved accuracy of results (Gee at al. 2002; Jabro et al. 2008).

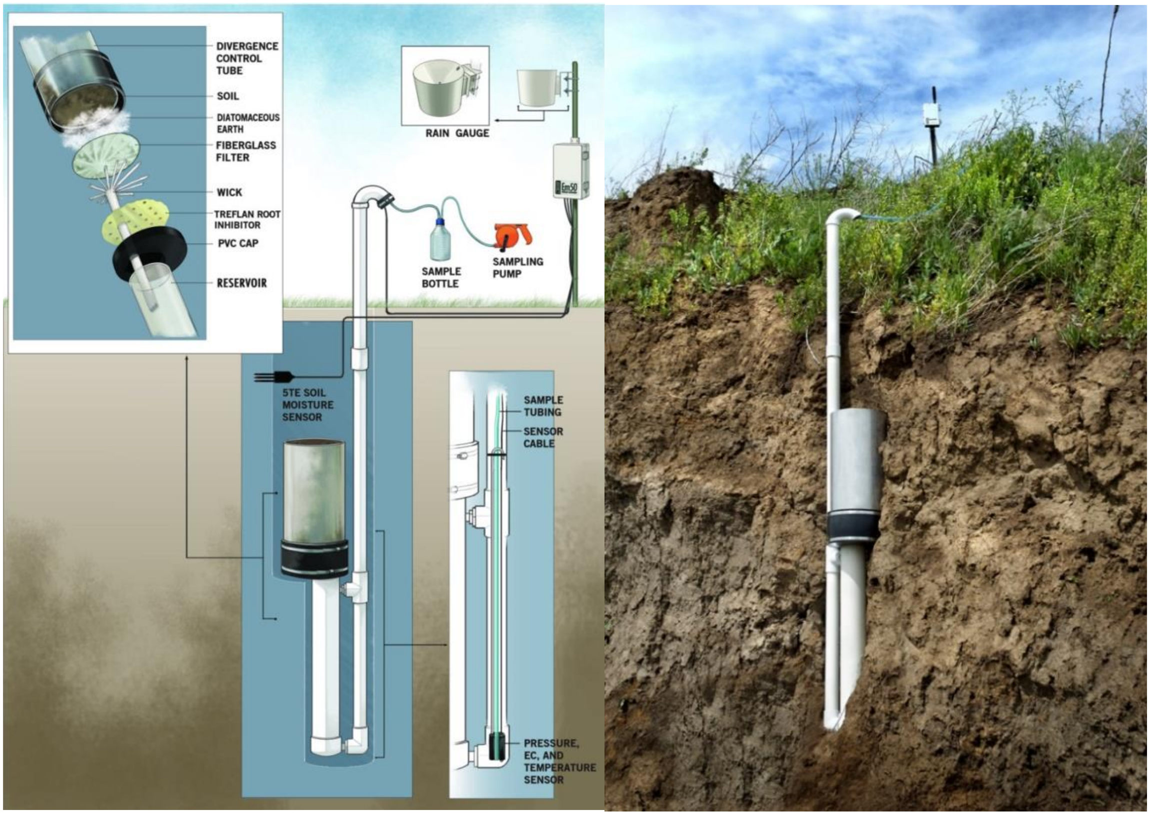

Figure 3.8. Components of the drainage lysimeter and their location with relation to each other (Decagon Devices Drain Gauge G3 manual, 2018).

The 1 m depth to which the drainage lysimeters were installed was due to most root growth of potato crops generally being confined to the top 40 to 60 cm soil layer (Ahmadi et al. 2011; Rykaczewska 2015). Therefore, the soil solution collected by the lysimeter was assumed to be the water and nutrients that had drained beyond the effective rooting zone and could not be taken up by the roots. For installation of drainage lysimeters, the planted seed tubers or young potato plants were carefully removed and a pit was dug to a depth of 40 cm (Figure 3.9), where the DCT was placed to collect an undisturbed monolith of soil (40 – 100 cm depth). The location selected for the monolith collection was not the final destination where the lysimeter was placed, but ~5 m to the side. The DCT was carefully hammered into the soil, dug open around the edges and blocked at the bottom to remove an undisturbed soil core. A separate pit was dug to a depth of 1 m where the lysimeter was installed.

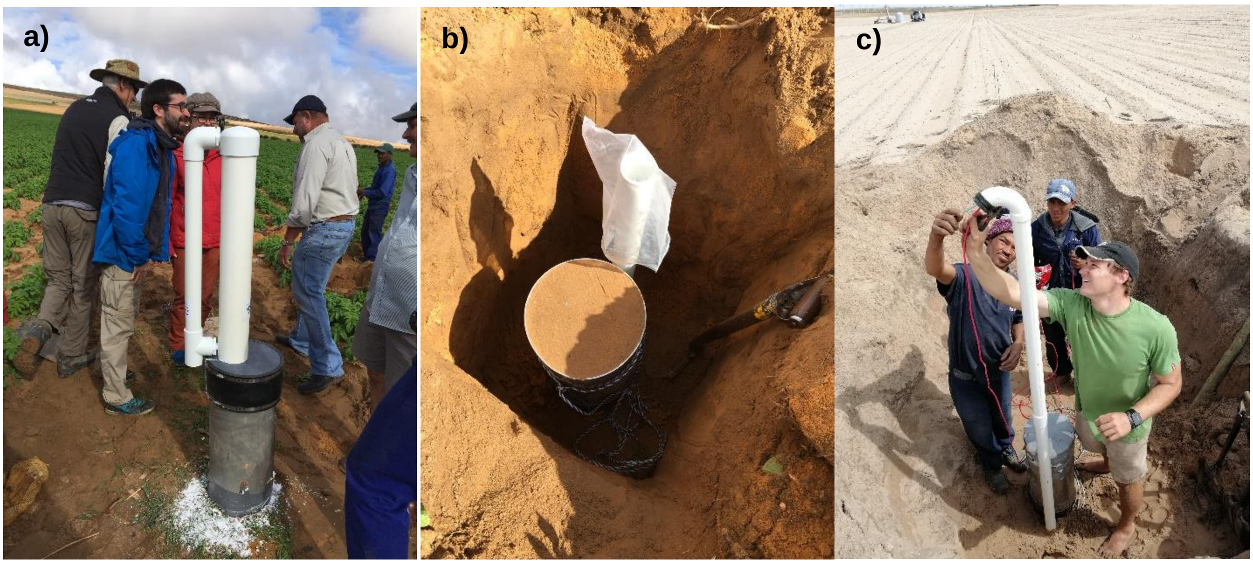

Figure 3.9. Installation of the drainage lysimeter. a) final assembled lysimeter placed upside down prior to installation to protect the fibreglass wick from bending or snapping; b) lysimeter sitting in its final location before being buried and tubers replanted; c) installation of the drainage sensor and suction pipe before refilling the pit.

When the 1 m depth was reached, a hole with 25 cm diameter was augured to a final depth of approximately 185 cm (from original soil surface) to facilitate the extension tube containing the hanging fibre glass wick. Diatomaceous earth was added to the bottom of the DCT to improve contact with the fibreglass wick. All components were attached and a rope fastened to the bottom side of the DCT where it attaches to the fibreglass wick and reservoir. The equipment was carefully lowered into the hole, ensuring the DCT was placed in the original potato row and not the furrow. Thereafter, the soil was carefully placed back into the pit in the same order it was removed and the tubers re-planted into rows on top of the lysimeter with the same inter-row spacing. A water depth and EC sensor were lowered to the bottom of the drainage lysimeters extension tube to measure the depth, temperature and EC of collected drainage water at half-hourly intervals. This data was recorded by an EM50 Meter-group datalogger that was connected to the sensor. Drainage solution (D_c) was removed every fortnight from the drainage lysimeters using a suction pump (mm). Conversion (from mL to mm) of solution sucked out (S_c) was made (Equation 3.16)[2], taking into account the area of the DCT (cm^2).

$$D_c = \left(\frac{S_C}{A_{DCT}}\right) \times 10 \tag{3.16}$$

Samples from the drainage lysimeters were collected fortnightly with the use of a suction pump. The pump was connected to extraction tubes protruding from the standpipes and the water volumes collected were placed into 500 mL bottles, taken back to the lab and the collected volume measured accurately. The samples were stored at 4°C and sent to a lab for nutrient analyses at a later date. Nutrient analyses results included pH readings as well as macro- (NH_4-N, NO_3-N, Ca, Mg, K, Na, SO_4 and H_2PO_4 in mg L^{-1}) and micronutrients (Fe, Mn, Cu, Zn and B in µg L^{-1}, and Cl in mg L^{-1})[3]. These results were converted to kg nutrient per hectare using Equation 3.17.

$$N_S = D_c \times N_C \tag{3.17}$$

where:

N_s is the amount of nutrient leached in kg ha^{-1};
N_C is the quantity of nutrient leached per m^{-3} of drainage water;
D_C was converted from mm to m^3 for the calculation and multiplied by 10 000 in order to quantify the leaching per hectare.

3.9 Soil sampling

Soil samples were collected at three depths using a hand auger: 0 to 30 cm, 30 to 60 cm and 60 to 90 cm at the beginning of each crop cycle as well as during yield analysis, seven to ten days prior to field harvest. The first soil samples were collected during the installation of the other equipment about two to three weeks after planting had taken place. For sampling, the field was split into quarters and within each quarter, six random sub-samples were taken (three samples taken between the row and three samples on the plant row) and mixed to give a representation of the entire quarter of the field. Samples were sent for standard soil analyses, including exchangeable acidity, pH_{KCl}, and macronutrient status. Nutrient contents were then converted from mg kg^{-1} to kg ha^{-1} using Equations 3.18 and 3.19.

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[2] 1 ml cm^2 = 10 mm; $Area_{DCT}$ is 506.7 cm^2

[3] To calculate the amount of nutrient leached in kg ha^{-1}, mg L^{-1} was converted to kg m^3 and drainage from mm to m^3.

Due to pre-planting fertiliser applications, nutrients from these additions were already present in the soil before sampling. Fertiliser applied before sampling was assumed to reflect in the soil analysis results and were therefore, deducted from results obtained by the soil analysis.

$$W_s = B_\rho \times D \times 10\ 000 \tag{3.18}$$

$$S_N = W_s \times N_{CT} \tag{3.19}$$

where:

W_s is the mass of a hectare of soil to a depth of 90 cm (kg ha^{-1});

B_ρ is the bulk density of the soil calculated during the soil analysis (kg m^3);

D is the depth soil samples were taken too (m);

S_N is the nutrient content present in the soil (kg ha^{-1});

N_{CT} is the nutrient content from the analysis (ppm or mg kg^{-1}).

3.10 Interception of solar radiation

Fractional interception (FI) of solar radiation was calculated from photosynthetically active radiation (PAR) measurements taken with an AccuPAR LP–80 ceptometer (Equation 3.20). Radiation levels were measured every fortnight, weather permitting, during cloudless days. Three random locations in each field's quarter was used, giving twelve readings per field. At each location one reading was recorded above canopy and two below canopy. The readings below canopy were taken in different rows within the same vicinity. The below canopy readings were taken by placing the ceptometer diagonally from the centre of one ridge to the centre of the neighbouring ridge and from the two readings at each site an average was taken (Figure 3.10).

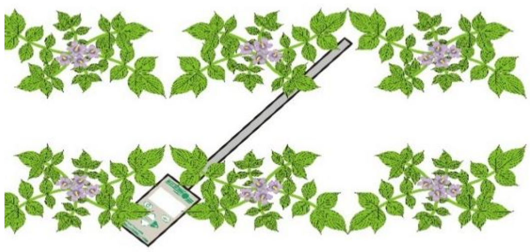

Figure 3.10. Illustration of the measurement of light interception with a ceptometer (illustration by C du Raan). Below-canopy measurements are taken from the centre of one row to the centre of the next row. Measurements above the canopy are taken facing north so as to not cast a shadow over the instrument.

$$FI = 1 - \frac{PAR(below)}{PAR(above)} \tag{3.20}$$

Crops were monitored throughout their growth cycles for any signs of visual deficiencies as well as any incidences of pests and diseases. Field 1 was infected by late blight (*Phytophthora infestans*) and Field 9 during the middle of its growth period had light green leaf colouring. Nothing notable, however, was reported in the other fields and crop growth was good.

The solar radiation data obtained is not discussed in the results and discussion section, refer to Appendix IIIb.

3.11 Nutrient content in plant matter

Leaf analysis was carried out, which commenced approximately one to two weeks after emergence, when the crop was established, and was conducted roughly every four weeks (every 2nd site visit) until crop desiccation. Ten leaves were collected randomly in each quarter of the field to give a representative sample of each field. The representative samples were therefore, made up of 40 leaves per field during each collection. Leaves were rinsed with de-ionised water to remove any chemical or fertiliser residues and dried in an oven at 60°C for seven days, removed and sent to a lab for standard nutrient analyses, including N, P, K, Ca, Mg, S (%) and Na, Fe, Mn, Cu, Zn, B (mg kg^{-1}).

The haulm nutrient content was only calculated for Fields 8 and 9 by cutting the aboveground plant parts at the soil surface just prior to senescence. The removal of two times 1 m strips randomly selected from each quarter of the field was carried out. Giving a total of 8 m from which above ground plant biomass was removed. The removed residue was then dried at 60°C for seven to ten days, milled and sent to a lab for nutrient analysis. The results were then converted from % to kg ha^{-1} using the known row spacing and area of removed biomass. The results for Fields 8 and 9 were very similar. The assumption that the haulm nutrient content, from the average values between Fields 8 and 9, was the same for the variety Sifra and FL2108 was made to estimate total plant nutrient removal for all fields. The nutrient content of the root systems was assumed negligible.

3.12 Tuber nutrient content and nutrient use efficiency

The amount of nutrients removed by tubers (T_c) from harvest was calculated using the tuber pith nutrient content and DM yield (DM_y) (Equation 3.21). The nutrient content (%) of the pith N_p alone was used as the nutrient removal by tubers due to the weight of the skin and medulla being negligible in comparison.

$$T_c = N_p \times DM_y \tag{3.21}$$

Nutrient uptake efficiency, nutrient utilisation efficiency and nutrient harvest index (NHI) was calculated using tuber and haulm nutrient contents (plant nutrient removal) in kg ha^{-1}, nutrient application through water and fertiliser and DM_y (kg ha^{-1}) (Zebarth et al. 2004; Trehan, 2009; Kolodziejczyk 2014; Tiemens-Hulscher et al. 2014; Gitari et al. 2018) (Equations 3.22, 3.23 and 3.24).

$$NU_pE = \frac{Nutrient\ removal_{(tuber+haulm)}}{Nutrient\ additions_{(fert.+water)}} \tag{3.22}$$

$$NU_tE = \frac{DM_y}{Nutrient\ removal_{(tuber+haulm)}} \tag{3.23}$$

$$NHI = \frac{Nutrient\ removal\ of\ the\ tuber}{Nutrient\ removal\ of\ the\ haulm} \tag{3.24}$$

where:

NU_pE and NU_tE is given as a ratio (kg kg^{-1}) and NHI as a %.

3.13 Tuber yield and quality

At the end of each growing season, tuber yield (Equation 3.25) and SG were determined. Within each quarter of the field, one row of 10 m length at two randomly designated positions was harvested, giving a total of eight 10 m row-length samples. However, for Field 8, due to the small field size (2.3 ha), 5 m strips were measured. All the tubers within the measured row were removed, classed according to their sizes and weighed. Classes included baby (5–50 g), small (50–100 g), medium (90–170 g), medium-large (150–250 g) and large (>250 g). From each harvested strip, 10 randomly selected medium-sized tubers were placed into a paper bag and taken to the laboratory for quality analysis. In total 20 medium-sized tubers were removed from each quarter, giving a total of 80 tubers removed for analysis per field. Tubers were rinsed in tap water to remove any soil fixed onto the tuber surfaces. Specific gravity was determined and calculated according to Schippers (1976), after which tubers were rinsed in de-ionised water to remove any residual chemicals or fertilisers. Specific gravity results obtained by Simba Ltd were also noted for each field on which the variety FL2108 was grown in order to check the accuracy of the equipment used in the lab to measure SG. Results given by Simba were more accurate and hence an average specific gravity of 1.083 was used in the study for that variety, from those results. Tubers were then air dried for five to ten minutes to remove water and processed. The first step of processing was to remove the skin of each tuber using a hand-held potato peeler, the medulla was then removed by peeling the layer below the skin twice around the circumference of the tuber. Tubers were then chopped into thin slices to sample the pith. All sections (skin, medulla and pith) were kept separate throughout. Samples of each section for each quarter where then put into a paper bag and placed into a drying oven at 60°C for seven days. Once dried, samples were removed, milled and sent to a lab for nutrient analysis. These results were then used during nutrient balance calculations.

Actual tuber yields were compared to the LINTUL DSS potato model (Haverkort et al. 2015) simulations to assess the yield gap and identify yield-limiting factors.

Fresh tuber yield (T_y) in t ha^{-1} was calculated using Equation 3.25:

$$T_y = \left(\frac{A_{ha}}{R_w \times R_L}\right) \times T_w \tag{3.25}$$

where,

A_{ha} is the area of 1 ha in m^2;
R_w is the row width (m);
T_w is the tuber mass collected within the sampled row length R_L (m).

From these results tuber DM yield (kg ha^{-1}) (Equation 3.26) was calculated using a DM content (DM%) of 21.7 and 20.9 for FL2108 and Sifra, respectively. The DM percentage for the variety Sifra (Fields 8 and 9) was determined by randomly selecting five medium-sized tubers per strip during the yield analysis sampling. The tubers were weighed (kg), chopped up and dried at 60°C for seven days and weighed again (Equation 3.27). However, this was not conducted for fields where FL2108 was grown. The SG results obtained for this cultivar were used to calculate DM percentage using a conversion table (Agriculture Victoria 2010; Haverkort 2018).

The DM_y was then used to calculate nutrient use efficiency (NUE) (kg kg^{-1}) (Equation 3.28) for each macro element. Nutrient use efficiency is the amount of tuber DM (kg) produced per kg of nutrient applied via fertiliser and water ($N_{(fert+water)}$).

$$DM_y = \%DM \times T_y \tag{3.26}$$

$$\%DM = \frac{Dry\ tuber\ mass}{Fresh\ tuber\ mass} \times 100 \tag{3.27}$$

$$NUE = \frac{DM_y}{N_{(fert+water)}} \tag{3.28}$$

The agronomic use efficiency (AUE) (kg kg^{-1}) (Equation 3.29) was also calculated using fresh tuber mass and nutrient application (kg ha^{-1}) through fertiliser alone (N_{fert}). The equation was modified from literature (Dobermann 2005; Abbasi et al. 2011; Gholipouri and Kandi 2012; Hu et al. 2014), as this study did not include a control crop with no fertiliser application.

$$AUE = \frac{T_y}{N_{fert.}} \tag{3.29}$$

3.14 Weather data

Daily weather data (temperature, relative humidity, solar radiation, wind speed and rainfall) was recorded using automatic weather stations. Stations were set up prior to the study on the farms where Fields 1, 3, 4, and 8 were located. Campbell Scientific automatic weather stations were set up on all other farms containing fields of study (Fields 2, 5, 7 and 9), except Field 6. The data used for Field 6 was collected from a nearby weather station belonging to the Agricultural Research Council (ARC). Set up stations included CRX10 or CR300 series dataloggers with manual connection as well as telemetry. Any missing data due to delayed installation of weather stations was filled in using other weather stations in the nearby vicinity of the fields.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Evaluation of irrigation systems

The efficiency values for the different Sandveld pivots are presented in Table 4.1. The average CU_{HH} obtained in this study was 88%. The minimum acceptable norm for this parameter is 85% (Heerman and Hein 1968). The maximum CU_{HH} obtained was 93% (Field 4) and the minimum 81% (Field 2). All fields thus, performed above the acceptable norm for this parameter, with the exception of Field 2 and Field 5, which also performed poorly in terms of DU_{lq} at 72 and 70%, respectively (acceptable norm is ≥75%). An average DU_{lq} of 80% was obtained in this study and a maximum of 89% (Field 4), suggesting generally good application uniformity in the region. The results obtained for CU_{HH} and DU_{lq} align with values reported in. Clemmens and Dedrick (1994), ranging from 78 to 90% for DU_{lq} and 86 to 94% for CU_{HH} and are within the recommended norms of >85% CU_{HH} and >75% DU_{lq} as reported by Savva and Frenken (2002) and Reinders (2013)

The AE for Fields 2, 6 and 8, given in red (Table 4.1), indicate values below the acceptable norm of 80% (Reinders 2013). However, Clemmens and Dedrick (1994) suggested that a well-designed centre-pivot irrigation system has an AE ranging from 75 to 90%. For the fields with low AE the actual application of water during each irrigation cycle, therefore, differs to that of the farmer's knowledge and can be influential on overall yield and water applied. For Fields 2, 6 and 8 substantial proportions of the water that entered the pivot's centre did not reach the soil surface (24, 23 and 36%, respectively). For Field 2 the low AE, along with low CU_{HH} and DU_{lq} values elucidates the need to over irrigate by approximately 25% to ensure that all parts of the field received sufficient water to attain acceptable yields. Similarly, Field 6's low AE could be attributed to the very low pressure (50 kPa) measured at the last tower (normal pressures can range from 70 kPa to 500 kPa, depending on sprayer type). The low pressure resulted in a gross application of 5.3 mm of water when the control panel was set for 10 mm. A decrease in pressure below the manufacturer's range has a negative effect on the uniformity coefficient (Zhang et al. 2013b). In contrast, during the evaluation of Field 8's centre-pivot system, climatic conditions influenced the overall AE. Due to the pivot's sprinklers hanging quite a distance from the soil surface, the high winds that occurred during the assessment, resulted in the erratic spread of water. The wind during the system evaluation was recorded at 20.4 km h^{-1}, while wind speeds below 18 km h^{-1} are preferred during an assessment. The effect of wind drift on water losses was assessed by Playán et al. (2005). The study conducted in Spain concluded that wind drift and evaporation losses amounted to

15.4 and 8.5% for day and night irrigation, respectively. However, this study was conducted on sprinkler solid-sets. Frequent high winds are an issue in the Sandveld area and therefore, the dropping of nozzle heights and selection of appropriate nozzle types may increase AE.

Table 4.1. Efficiency parameters of centre-pivot irrigation systems as well as the average flow rates of water and rotation times taken to complete one cycle at 100% of the systems speed.

Type	Field	CU_{HH} (%)	DU_{lq} (%)	AE (%)	Flow rate (m^3 h^{-1})	Rotation time (h)	Area (ha)
Norm		**≥85**	**≥75**	**≥80**			
Extensive	Field 1	91	84	89	90	6.5	25.61
	Field 4	93	89	99	85	6.9	20.81
	Field 6	89	84	77	67	6.8	20.28
Intensive	Field 2	81	72	76	70	4.4	11.22
	Field 3	89	79	96	81	7.5	20.36
	Field 5	84	70	99	74	5.2	11.73
	Field 7	88	83	93	93	6.6	20.9
	Field 8	91	86	64	14	2.4	2.27
	Field 9	85	76	93	72	6.5	19.67
Average		**88**	**80**	**87**	**72**	**6**	**17**

Values in red are below the acceptable norms as stated in literature (Savva and Frenken 2002; Koegelenberg and Breedt 2003; Reinders 2013). CU_{HH} refers to the coefficient of uniformity (Heerman and Hein), DU_{lq} is the distribution uniformity of the lowest quarter and AE refers to the application efficiency.

From the results obtained in the Sandveld it is evident that various factors play a role in the efficiency of an irrigation system such as design, climatic and managerial aspects. The manufacturers operating pressure and sprinkler height of centre-pivot irrigation systems plays a key role in the system efficiency.

The majority of the fields had acceptable irrigation system efficiencies, which indicated relative uniform application of water across Sandveld fields. Over- or under-irrigation generally did not occur because of faulty sprinklers. Under current practices, irrigation system evaluations are non-existent. The evaluation of pivots is only conducted during purchase and installation by the manufacturer or irrigation agent. The use of brackish water and harsh climatic conditions, however, will cause a rapid deterioration in pivot structures, affecting the efficiency of water application negatively. Therefore, the need to periodically evaluate system efficiencies and correct inefficient parameters to meet the upper limits of the acceptable norms discussed in the literature is evident. The ARC (2004) suggests the evaluation of centre-pivots after every growing season (annually), to protect the pivot during months when it is not in use and ensure minimal problems at the start of the following season. The improvements will not only decrease unwanted water losses and improve the accuracy of water application, but improve the WUE of potato production. The brackish water can result in the rapid corrosion of galvinised piping used for centre-pivot irrigation structures. The potential reasons contributing to corrosion are caused by the use of water with a low pH leading to acid corrosion as it causes a rapid attack of Zn coating within the pipe's inner walls and mechanical wear can result from substantial solids suspended in the water. In certain cases, farmers in the Sandvled with poor irrigation water quality have fixed a polyvinyl chloride pipe along the top of the main booms' original galvinised pipe (Della Rovere et al. 2013). The water is then run through the polyvinyl chloride pipe instead of the main pipe to increase the pivot's lifespan. However, water quality was only measured once for each field throughout the season and the periodic evaluation throughout the season is required to observe the change in water quality throughout the season as farmers in the Sandveld irrigate from various water sources throughout growing periods.

4.2 Drainage and leaching

4.2.1 Water inputs and losses

Figure 4.1 gives a comparison between the total volumes of water (mm) applied during the cropping season of each field under surveillance. Results are according to the electromagnetic flow meter and pressure transducer measurements. Water application for six of the nine fields according to the pressure transducers were slightly lower (average of 4.5% less) than that of the flow meters, with the exception of Fields 3, 8 and 9 (average of 6.4% higher). The comparison suggests that using pressure transducers may result in a slight under- or over-estimation of total water use. However, due to the large capital investment required for electromagnetic flow meters with telemetry, the pressure transducers may still be considered as a cost-effective alternative (about 75% saving), with relatively good accuracy. The sequence of fields from left to right in Figure 4.1 follows the order of planting from the earliest to latest date and generally indicates an increase in irrigation amount with delay in planting date, with the exception of Field 6, which was affected by a shallow water table and Field 9, which was situated 200 m from the ocean, resulting in lower average summer temperatures at this location. Due to Field 9 being situated so close to the coastline, cool winds from the ocean blew over the field and often mist and fog was noted at this location.

Table 4.2 presents the planting date, total rainfall, irrigation and drainage amounts (for intensively monitored fields) recorded per field. In the Sandveld, one extensive (Field 1) and one intensively monitored centre-pivot (Field 2) were planted in March 2018, when conditions of higher temperatures and low rainfall prevailed (Figures 4.2 and 4.3 respectively). All relevant data for all the fields is presented in Table 4.2, while daily irrigation and rainfall amounts as well as cumulative drainage collected by lysimeters are presented in Figures 4.2 to 4.10. The producers of both Fields 1 and 2 irrigated frequently (daily) early in the crop growing season and decreased irrigation due to recurrent rainfall events occurring in the months of June and July. Field 1 received a total of 260 mm irrigation and 271 mm of rainfall, while Field 2 received 486 mm irrigation and 258 mm rainfall.

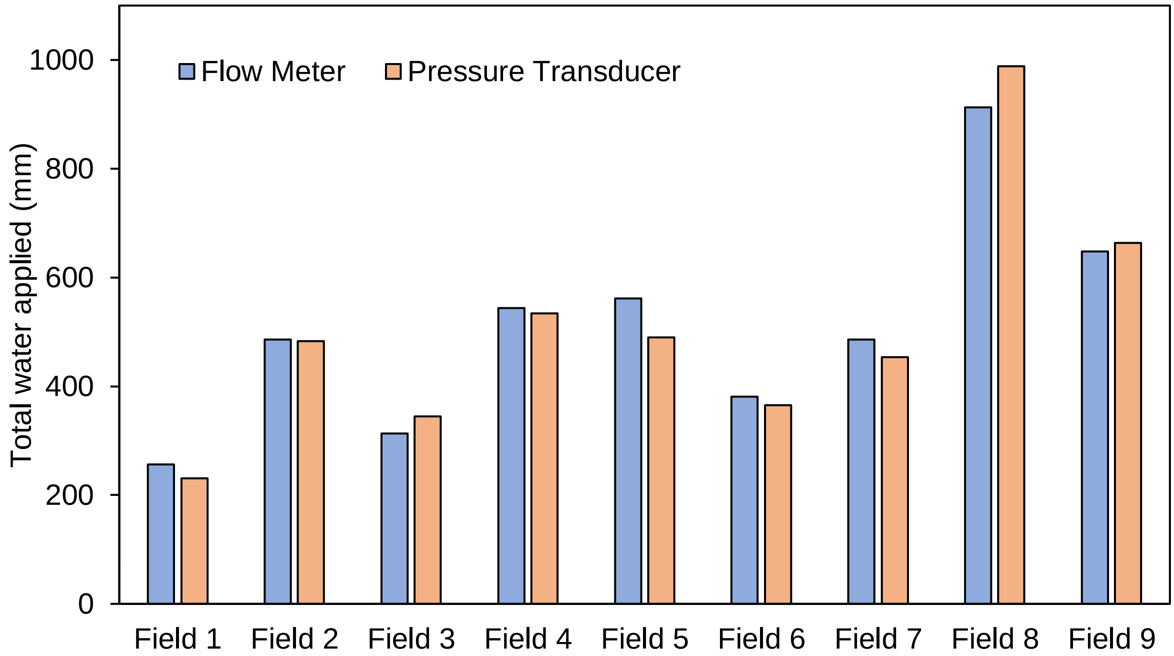

Figure 4.1. Total volumes of water (mm) applied during crop growth of each field under surveillance according to the electromagnetic flow meter and pressure transducer measurements.

During periods of rainfall and cool weather (low ET), drainage increased dramatically (Figure 4.3) due to very low water holding capacity and rapid drainage of the sandy soils. This, together with slight over-irrigation at times, resulted in a total cumulative drainage of 205 mm recorded for Field 2 (Table 4.2). When substantial water inputs (rainfall or irrigation) occurred during periods of low ET, drainage accumulation increased. This trend is observed throughout all fields where drainage was monitored (Field 2, 3, 5, 7, 8 and 9), with only one outlier (Field 7). Field 2 had a higher total water input than Field 3 (Figure 4.4). However, drainage accumulation was lower and the yield obtained was acceptable at 51.6 t ha^{-1}. In the Sandveld region with the variety FL2108, producers are aiming for a production of 50 t ha^{-1}. Note that the detailed yield results are presented in section 4.41 (Table 4.26)

Table 4.2. Total water inputs (rainfall and irrigation) and losses (drainage) recorded for the different Sandveld sites. Drainage was not measured at the extensively monitored fields.

Type	Field	Plant date	Rain (mm)	Irrigation (mm)	Drainage measured (mm)
Intensive	Field 2	28 Mar	258	486	205
	Field 3	2 May	232	313	296
	Field 5	27 June	143	562	74
	Field 7	31 July	71	486	4
	Field 8	11 Oct	54	913	233
	Field 9	30 Nov	36	648	302
Extensive	Field 1	3 Mar	271	260	-
	Field 4	25 June	155	545	-
	Field 6	9 July	154	381	-

Field 3 was planted in May, when temperatures were low (average of 17.2°C) and significant rainfall occurred. A total of 232 mm rainfall and 313 mm irrigation was recorded (Table 4.2, Figure 4.4). The increased frequency of irrigation by the farmer during July 2018 was attributed to by drier and hotter conditions than the preceding months (Figure 4.4). Substantial drainage of 296 mm was collected by the drainage lysimeter. However, most of this drainage occurred during cool, rainy periods. The yield obtained was lower than the target yield of 50 t ha^{-1} at 41.5 t ha^{-1}.

Fields 4 and 5 (Figures 4.5 and 4.6, respectively) were both planted late June 2018. Although planting occurred during mid-winter, substantially less rainfall (155 mm and 143 mm, respectively) was recorded, compared to the crops planted in May. Fields 4 and 5 grew into hot, drier summer months until harvest in mid-November. Only 74 mm of drainage was recorded for Field 5, with the majority of it occurring during periods of rainfall in September (Figure 4.6). Yields obtained were 57.5 and 49.8 t ha^{-1} for Fields 4 and 5, respectively.

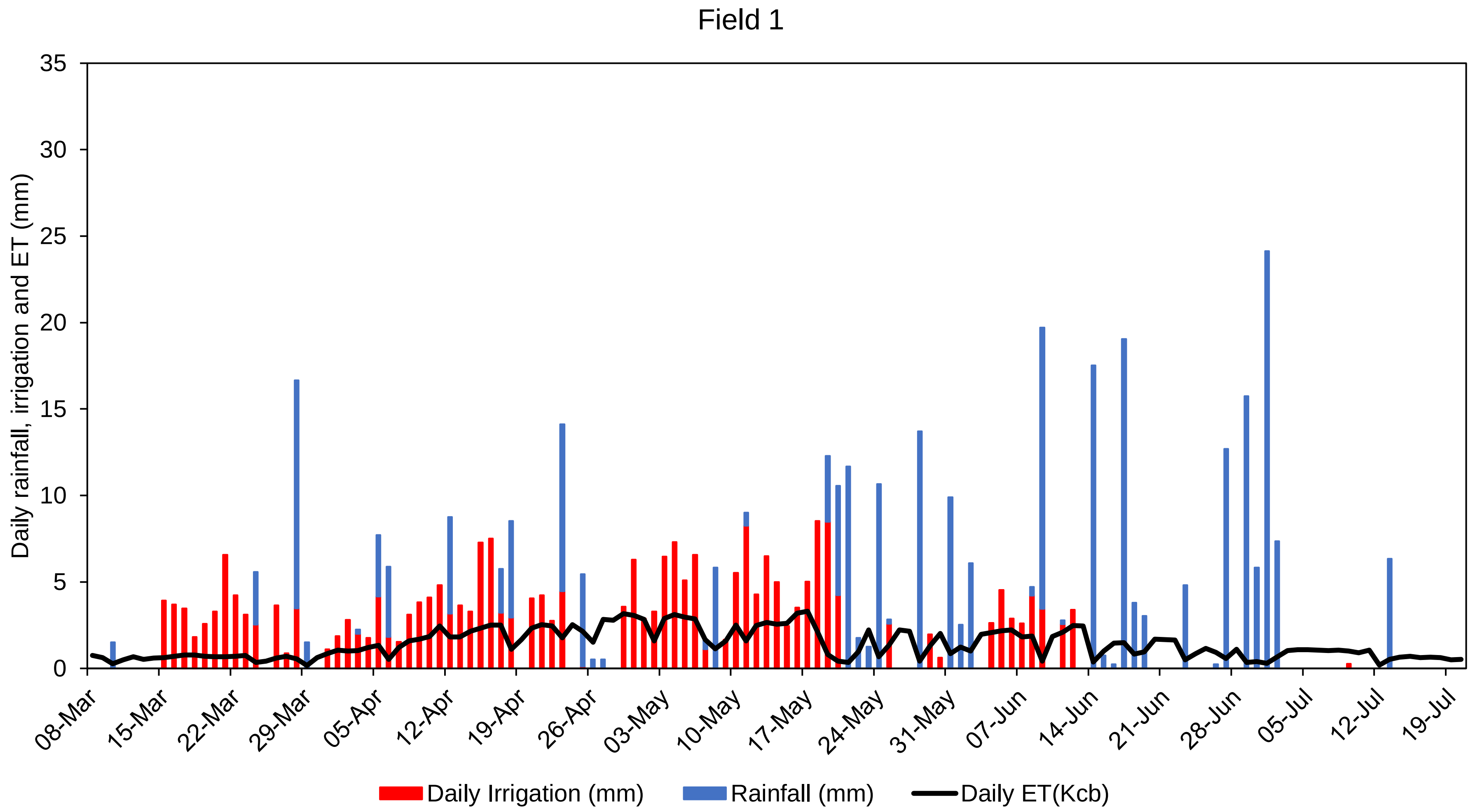

Figure 4.2. Daily fluctuations in water losses (drainage and ET) and inputs (rainfall and irrigation) during crop growth for Field 1 planted in autumn. The dates span from date of planting to date of harvest. The daily irrigation was terminated early due to late blight (*phytophthora infestans*) occurrence.

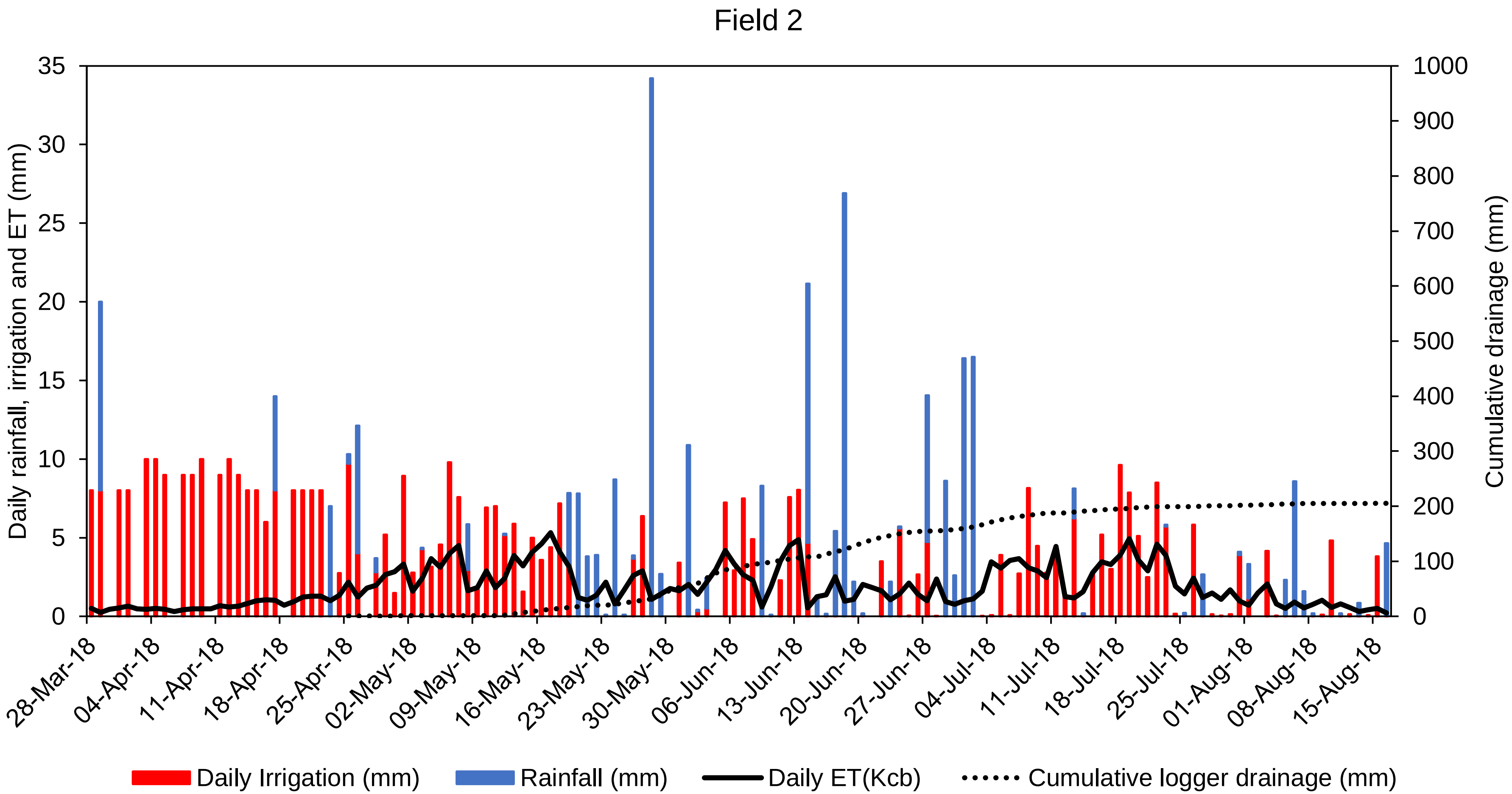

Figure 4.3. Daily fluctuations in water losses (drainage and ET) and inputs (rainfall and irrigation) during crop growth for autumn planted Field 2. The dates span from date of planting to date of harvest.

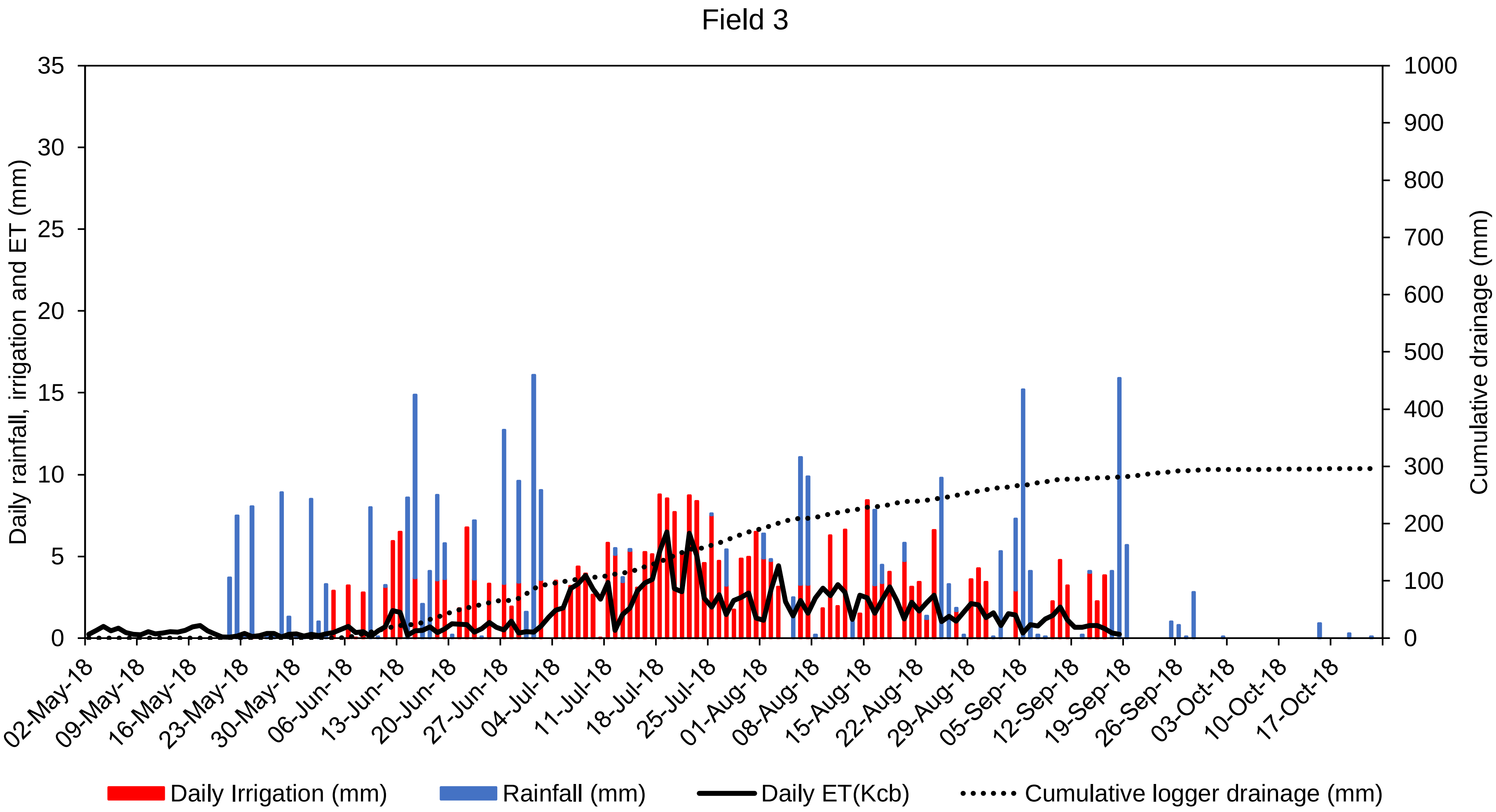

Figure 4.4. Daily fluctuations in water losses (drainage and ET) and inputs (rainfall and irrigation) during crop growth for autumn planted Field 3. The dates span from date of planting to date of harvest.

Field 6 and Field 7 (Figures 4.7 and 4.8, respectively) were planted in late June and the end of July respectively and were harvested mid to late November. The two crops received 154 and 71 mm of rainfall, respectively, throughout the cropping season. Crop water requirements were generally high due to growth occurring mostly throughout the hot and dry summer months from September to November, with October and November having average daily maximum temperatures (Appendix IIIa) of 30 ^{o}C and 28 ^{o}C, respectively, for the region. For Field 7, where the least rainfall occurred for the fields planted in July, a total of 486 mm of irrigation was recorded, which was similar to the water application of June planted fields. No substantial drainage occurred in this field, only 4 mm was measured by the lysimeter sensor (no drainage solution was removed by the suction pump) throughout the season in spite of the large irrigation amount. The low drainage can be explained by the little amount of rainfall received (71 mm), as well as the observation that the subsoil (0.5 – 1.0 m depth) was dry at the time of planting. It is, therefore, likely that the excess irrigation did not surpass the storage capacity of the soil profile and was thus used to refill the profile as the season progressed. The farmer consequently, had control over the majority of the water being applied to this field. The yield as well as the WUE (Table 4.8) obtained were high (53.9 t ha^{-1} and 96.7 kg mm^{-1} respectively). During crop growth, it was noted that canopy cover was incomplete and at various stages, vegetative growth lacked vigour. A possible explanation can be that the farmer under-irrigated during the vegetative growth stage and could have increased his irrigation frequency earlier on, potentially resulting in higher yields whilst maintaining a good WUE.

In Field 6 only 381 mm was irrigated. This lower irrigation amount as well as good WUE of 95.7 kg mm^{-1} (Table 4.8) can be explained by the presence of a clay layer at a 30 to 50 cm depth within the soil profile, which limited deep drainage, and created better utilisation of the higher rainfall (154 mm) recorded at this site. Total seasonal irrigation requirement was, therefore, less compared with other crops grown during the same time of year, as more water was held by the duplex soil. This indicates the positive influence on WUE of a limiting layer that curbed deep drainage (none of the other fields contained any form of clay layer within 1 m of the soil profile).

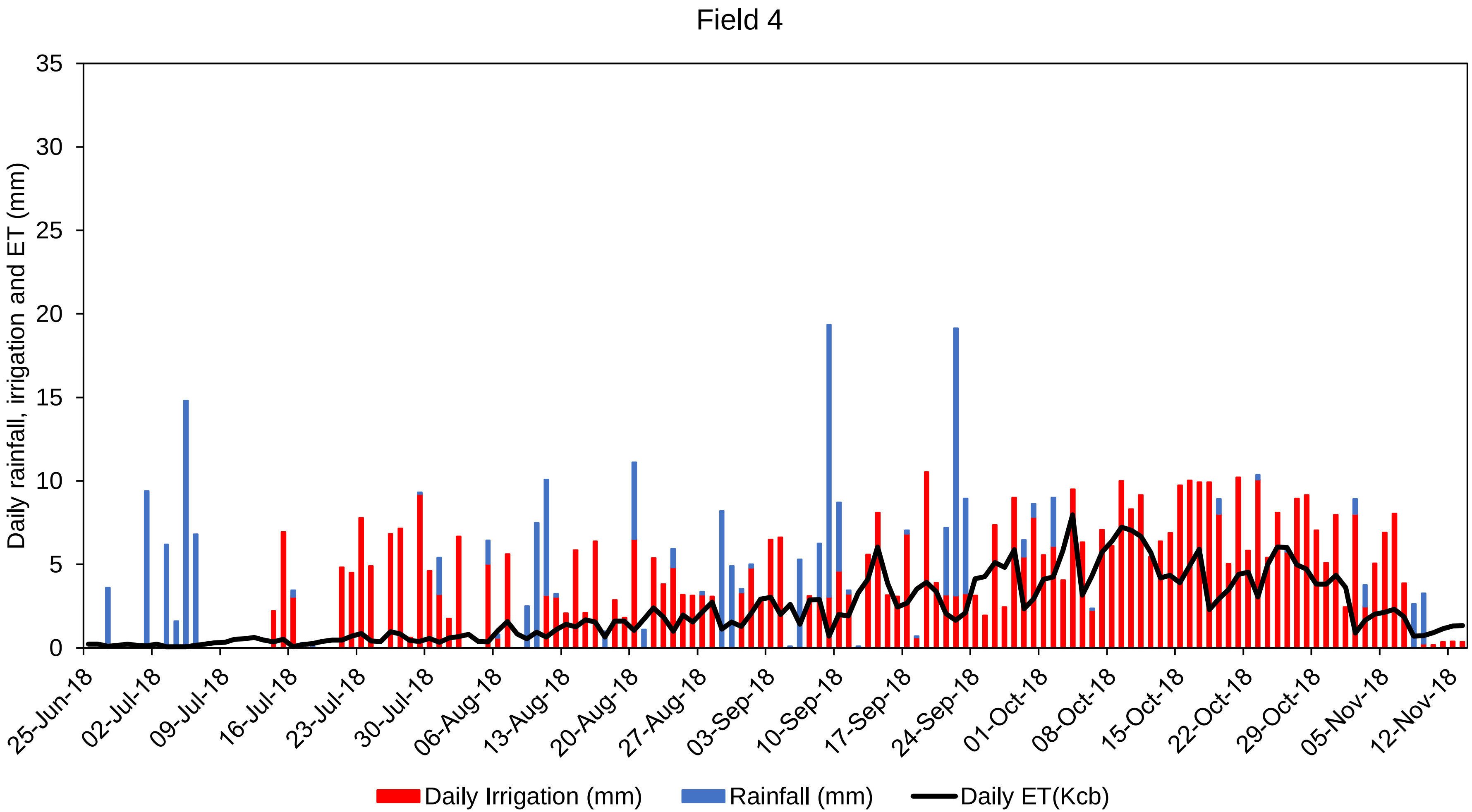

Figure 4.5. Daily fluctuations in water inputs (rainfall and irrigation) of Field 4 from planting (winter) to harvest. The irrigation frequency increased toward the end of the season during the end of September/beginning of October months due to an increase in temperature and ET demand.

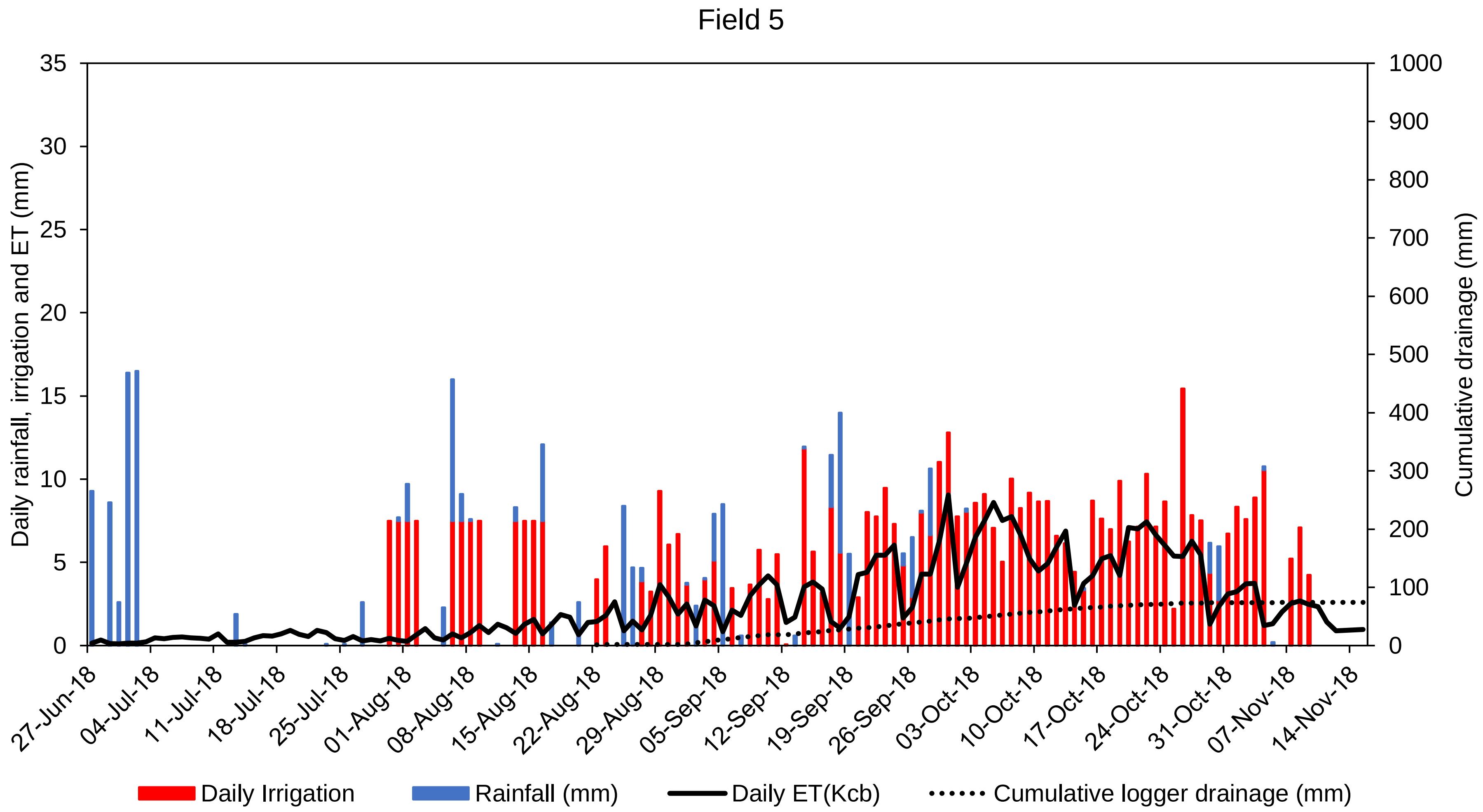

Figure 4.6. Daily fluctuations in water losses (drainage and ET) and inputs (rainfall and irrigation) during crop growth for Field 5. The dates span from date of planting to date of harvest.

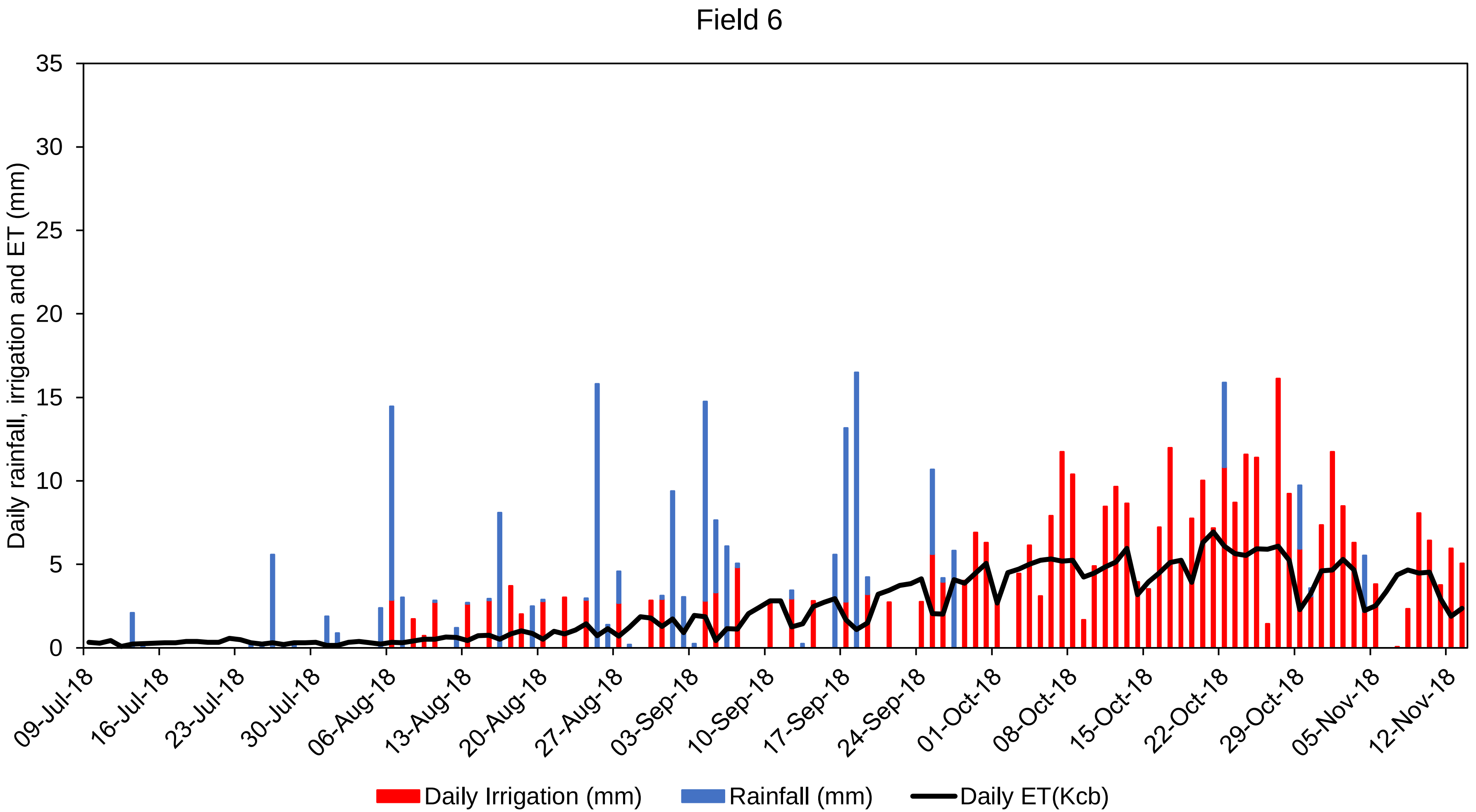

Figure 4.7. Daily fluctuations in water losses (drainage and ET) and inputs (rainfall and irrigation) during crop growth for Field 6. The dates span from date of planting to date of harvest.

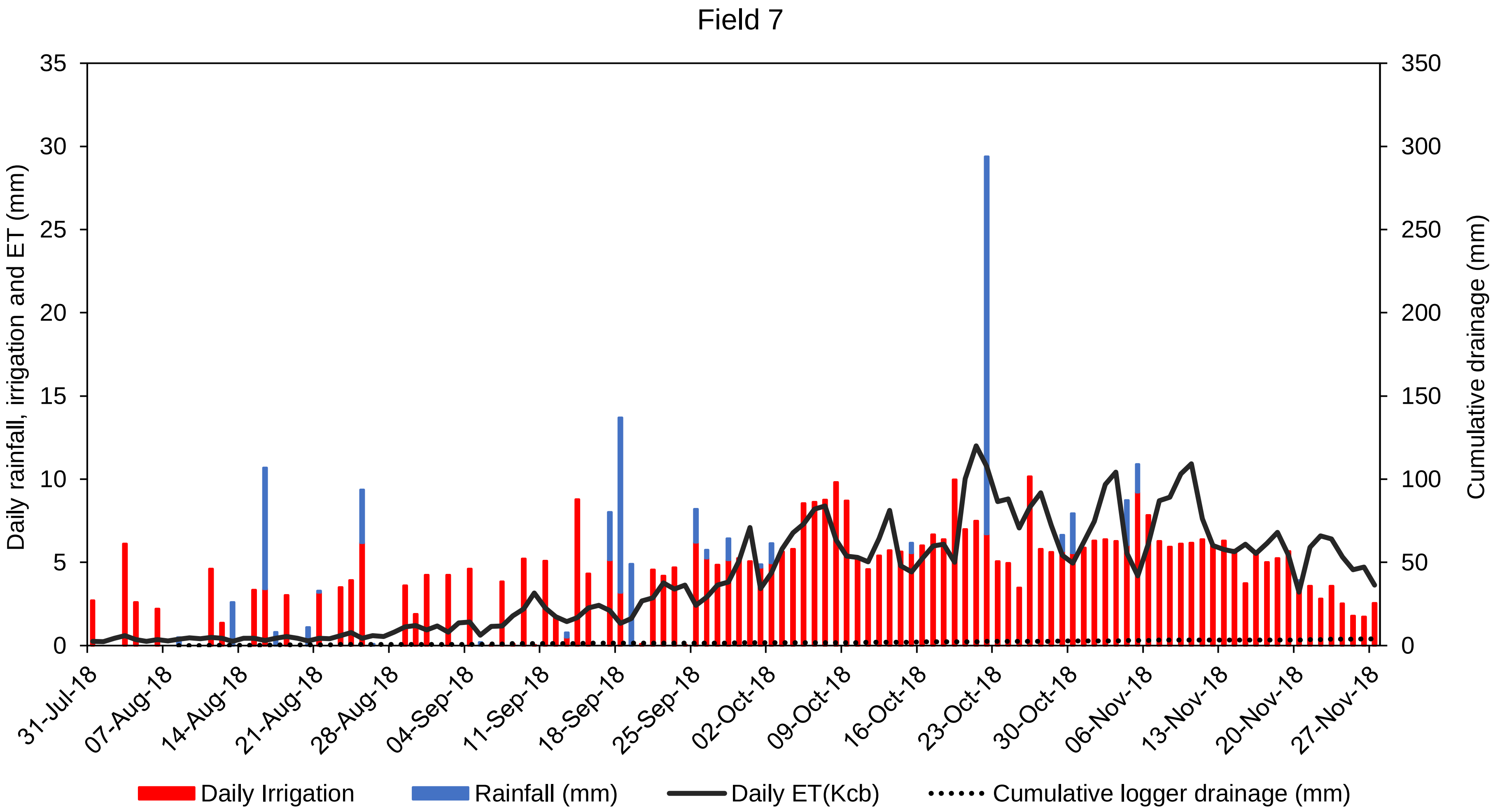

Figure 4.8. Daily fluctuations in water losses (drainage and ET) and inputs (rainfall and irrigation) during crop growth for Field 7 (winter planted). The dates span from date of planting to date of harvest.

The increase in drainage occurring over winter periods when ET demands are low and rainfall events more frequent corresponds to Kengni et al. (1994). However, in their study this was reported below a depth of 0.8 m during the intercrop period for maize when soils were bare and ET low. However, it was reported that 90% of the drainage occurring was a result of rainfall. This should be considered during early crop stages of winter planted fields before canopy cover is developed and majority of the soil is uncovered. Meissner et al. (2010) also indicated an increase in drainage accumulation caused by rainfall. Also noted was the effect of increased precipitation and water inputs on the tendency to over-estimate drainage accumulation when lysimeters functioning with a passive wick are used. The over-estimation was reported to occur in sandy soils in particular, due to the rise of a mismatch between the wick and soil suction.

It was hypothesised before the start of the study that summer planted fields would incur less drainage during the season than winter planted crops due to a lesser amount of rainfall occurring as well as higher temperatures and ET associated with the time of year. However, this was not always the case, as indicated by Figures 4.9 and 4.10. Both Fields 8 and 9 produced substantial drainage (233 mm and 302 mm respectively). On average, each irrigation application was higher than winter planted fields. Cumulative reference evapotranspiration (ET_o) over the entire growth period for Field 8 was high at 790 mm. Water applications of between 8 and 15 mm per irrigation cycle was applied to this field. Irrigation frequency for both fields was high. The growth period for Field 8 was 126 days of which irrigation was applied on 101 days. This can be attributed to the hot temperatures, high ET demand and windy conditions in summer months, resulting in producers applying irrigation frequently. The same trend is seen for Field 9. However, for Field 8 the AE for the centre-pivot was very low (refer to Table 4.1), which necessitated the application of more water than was required by the crop. Thus, over irrigation occurred to make up for the substantial loss of water between the nozzles and soil surface. The start of irrigation for Field 9 occurred on the 4th of December 2018 and continued until harvest. The dips seen in daily irrigation in Figure 4.10 are due to the halting of irrigation in order to apply chemical sprays, but once this was completed, irrigation continued. Generally, farmers practice pre-planting irrigation in the Sandveld and do not commence irrigation again until sprout emergence. The reason for drainage in summer months can be attributed to the high irrigation frequency early in the season. However, during the mid to late growth period of the crops, application frequency is not necessarily too high, but rather the irrigation amounts per irrigation cycle were too high. Just prior to crop emergence both producers started irrigating. Emergence occurs at a much faster rate in summer months and hence the profile still contains substantial water from pre-planting application. During the early crop development there is a large portion of bare soil, therefore evaporation from the bare soil surface is high. Once canopy cover starts to develop, less evaporation is occurring and transpiration increases. However, due to the large irrigation applications, more water is entering the soil profile than is lost via the process of ET, resulting in a build-up of soil profile water. Field capacity is eventually reached and exceeded, resulting in drainage accumulation. Drainage accumulation for Field 8 reaches 10.6 mm just 23 days after emergence. A total irrigation amount of 913 mm was applied to this field. However, for Field 8 it is evident that the substantial water application exceeding the crop water requirement resulted from the very low AE of the centre-pivot. Even though total accumulated drainage for the season was substantial, the yield for Field 8 was exceptionally high at 118.2 t ha^{-1} and contributed to an excellent WUE (122.2 kg mm^{-1}). Similarly, Field 9 produced a good yield of 59 t ha^{-1} and WUE of 86.2 kg mm^{-1}. For Field 9, a comparable trend is seen to Field 8. However, each irrigation application per cycle is lower than for Field 8, between 6 to 8 mm. This is due to a lower ET throughout the season (Field 9 was situated <1 km from the Atlantic Ocean), so less water is used by the crop. Irrigation frequency early in the season was high and field saturation was reached earlier, with a large accumulation of drainage being more notable quicker in this field than Field 8. At 23 days after emergence, Field 9 already accumulated 42 mm of drainage. Later in the season (13th of January onwards), drainage accumulation increased. This was attributed to high irrigation amounts. Throughout the season, a total of 44% of the water input into Field 9 by rainfall and irrigation was lost as drainage.

The over irrigation through high irrigation frequencies early in the season and substantial water application during summer planted fields is also used as a strategy in the Sandveld to prevent wind damage. The high winds in the area often pick up sand in the field, which moves through the crop causing a sand blasting effect. Thus, irrigation strategies to keep the surface wet prevent the movement of sand particles. This particularly contributed to the over-irrigation that occurred on Field 9, in an effort to curb wind damage through sandblasting of plants, especially late in the season when canopy cover started to drop.

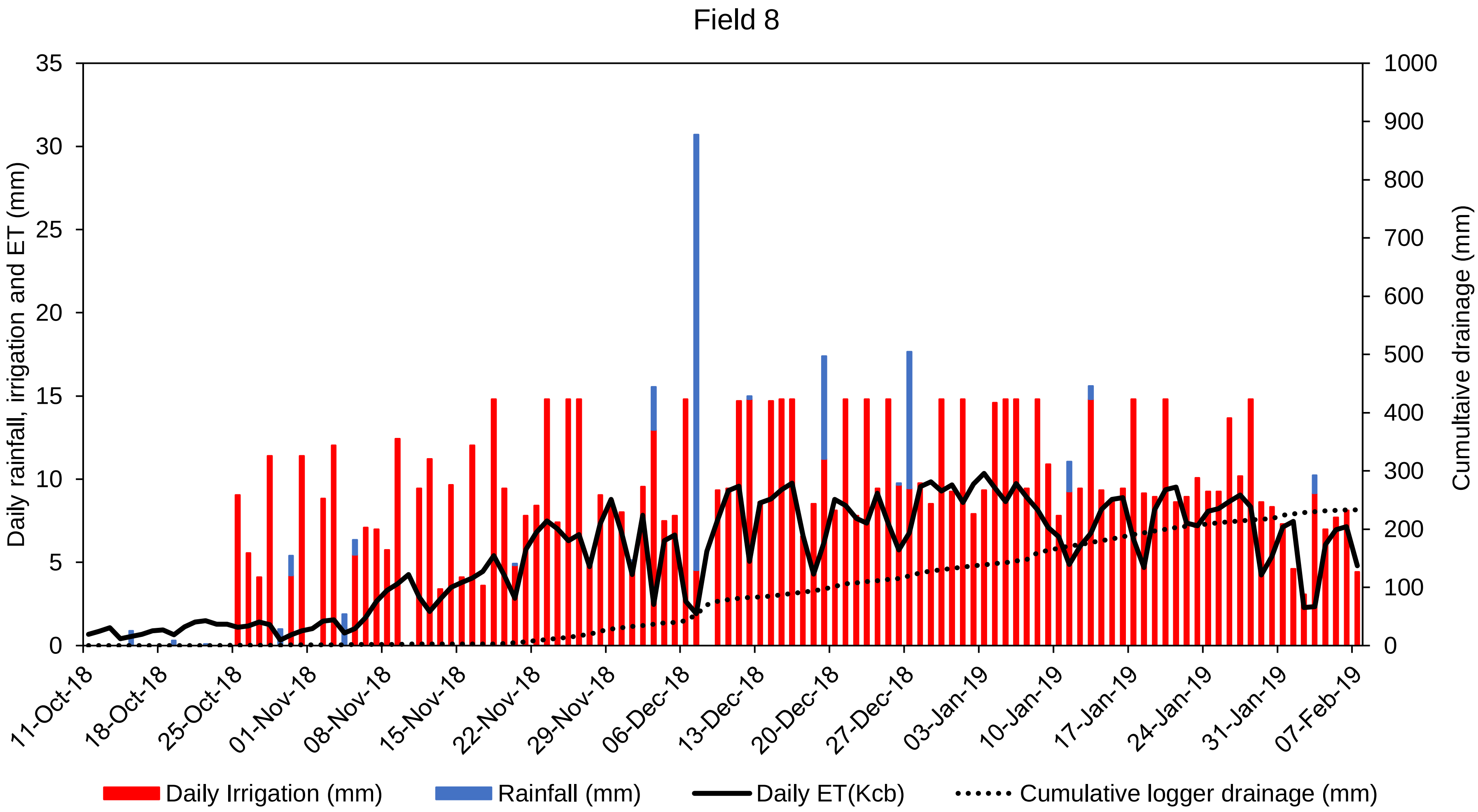

Figure 4.9. Daily fluctuations in water losses (drainage and ET) and inputs (rainfall and irrigation) during crop growth for Field 8 (summer planted). The dates span from date of planting to date of harvest.

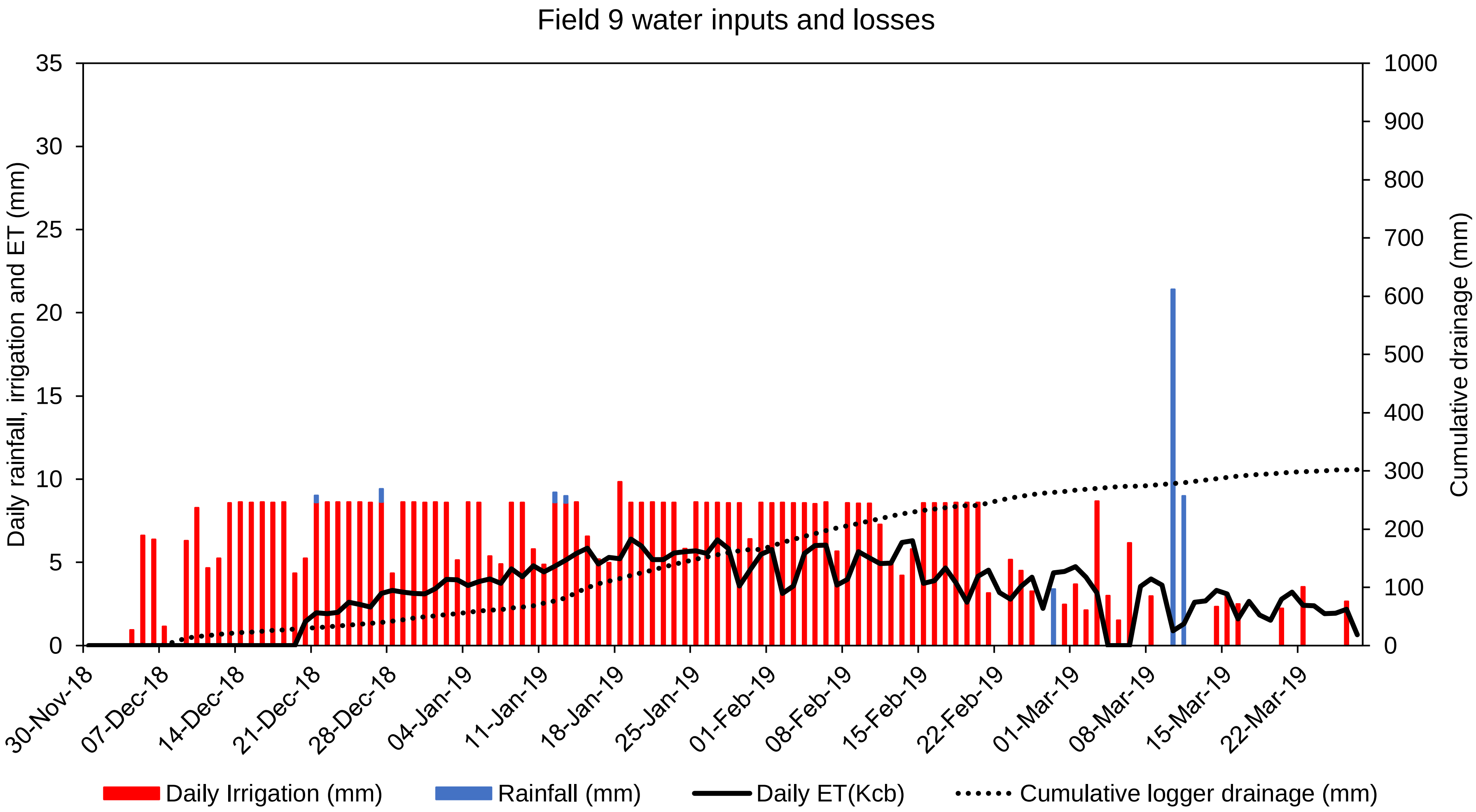

Figure 4.10. Daily fluctuations in water losses (drainage and ET) and inputs (rainfall and irrigation) during crop growth for a summer planted field (Field 9). The dates span from date of planting to date of harvest. Weather data is missing from date of planting until the 20th December.

The water application on all fields, with the exception of Field 9, was within the suggested range for good potato growth (Haverkort 1982; Kang et al. 2004, Fleisher at al. 2008; Parent and Anctil 2012). Only for Field 7, did low soil water potentially cause a difference between actual yield and potential yield (Table 4.26), but this effect was minor (actual yield was only 7% lower than potential yield). Irrigation scheduling in the Sandveld, however, is not altered according to plant physiological demands, as is suggested by Fabeiro et al. (2001). The reason being due to the sandy nature of the soil profiles, soils tend to dry out rapidly, which is not conducive to potato production as the crop is sensitive to water stress (Shock et al. 1998; Fabeiro et al. 2001; Yuan et al. 2003; Shock et al. 2007). Therefore, farmers tend to over-irrigate because of the fear that crops may suffer drought stress due to the low water holding capacity of the sandy soils. Thus, producers over irrigate to stay on the 'safe side'. Concerning drainage, the observations seen for all fields vary from that reported by Vázquez et al. (2005), which indicated that the greater drainage occurred during early crop development of vegetables due to a larger application of water than used by the ET demand. This difference is better observed in summer planted fields where rainfall does not play a substantial role. Drainage does occur early on, however; Field 9 shows a gradual increase in drainage during early crop development and a steeper cumulative drainage curve occurring towards the middle of the season from early January to the end of February due to the high application rate. This is also seen in Field 8, which indicates an increase in drainage accumulation in the second half of each growth period. Bošnjak et al. (2012) reported the positive correlation between water consumed by a potato crop and tuber yield. Fields in the Sandveld that produced little drainage showed an agreement with this statement. Field 7, which produced negligible drainage over the entire season, used water efficiently and produced a yield close to the potential yield as calculated by the LINTUL DSS potato model. Fields 3 and 9, on the other hand, incurred large amounts of drainage, resulting in lower yields produced compared to the simulated potential yields (Table 4.26).

4.2.2 Estimated water requirements

4.2.2.1 Basal crop coefficient curves

The basal crop coefficient curves (Figure 4.11) were calculated for each individual field monitored within the Sandveld. When producing the Kcb curves the assumption of uniform ideal crop growing conditions in each field was made (Jayanthi et al. 2007). The figures obtained in this study generally mimic the trend illustrated by Allen et al. (2005), Benli et al. (2006), Miao et al. (2016) and Mohktari et al. (2018). For autumn and winter planted fields such as Fields 1, 2, 3 and 4, where the time the crop was in the field extended >130 days, curves started to diverge from the typical Kcb curves depicted in literature (Allen et al. 1998). The divergence stems from the crop generally dying by 120 DAP. However, it is assumed ET ceases ≥140 DAP unless irrigation is applied if the crop is in the field longer than140 days. Hence, the graphical trend seen for Fields 2, 4 and 5. A similar curve was seen for mustard (*Brassica juncea*) by Gupta et al. (2017). The curves for crops grown during warmer periods follow the more typically depicted basal crop coefficient curve (Allen et al.1998). The warmer temperatures and higher solar radiation are conducive to rapid crop development and hence termination and harvesting of the crop occurred earlier at about 120 DAP.

The fields planted in March (autumn) had a shorter period from planting to emergence due to higher temperatures occurring during March and April (Figure 4.12 and Table 4.3). On the other hand, the fields planted in the middle of winter (May to early July) had longer periods between planting and emergence (Figure 4.12), extending from 28 to 33 days (Fields 3, 4, 5 and 6). The fields planted after the end of July had shorter periods between planting and crop emergence. The shortest period being 6 days (Field 9). The length and steepness of the curves in Figures 4.11 and 4.12 are dependent on climatic conditions. Between emergence and 100% canopy cover, winter planted crops (June to July) averaged 49 days, compared to autumn planted crops (March to April) which averaged 36 days (Table 4.3). The maximum length for June to July plantings was 52 days (Field 6). The summer grown Field 8, on the other hand, reached 100% canopy cover rapidly at 31 days. The duration period of 100% canopy cover was extended (52 days) in crops grown during warmer conditions with higher solar radiation (Figures 4.11 and 4.12), compared to those grown in winter periods (22 days).

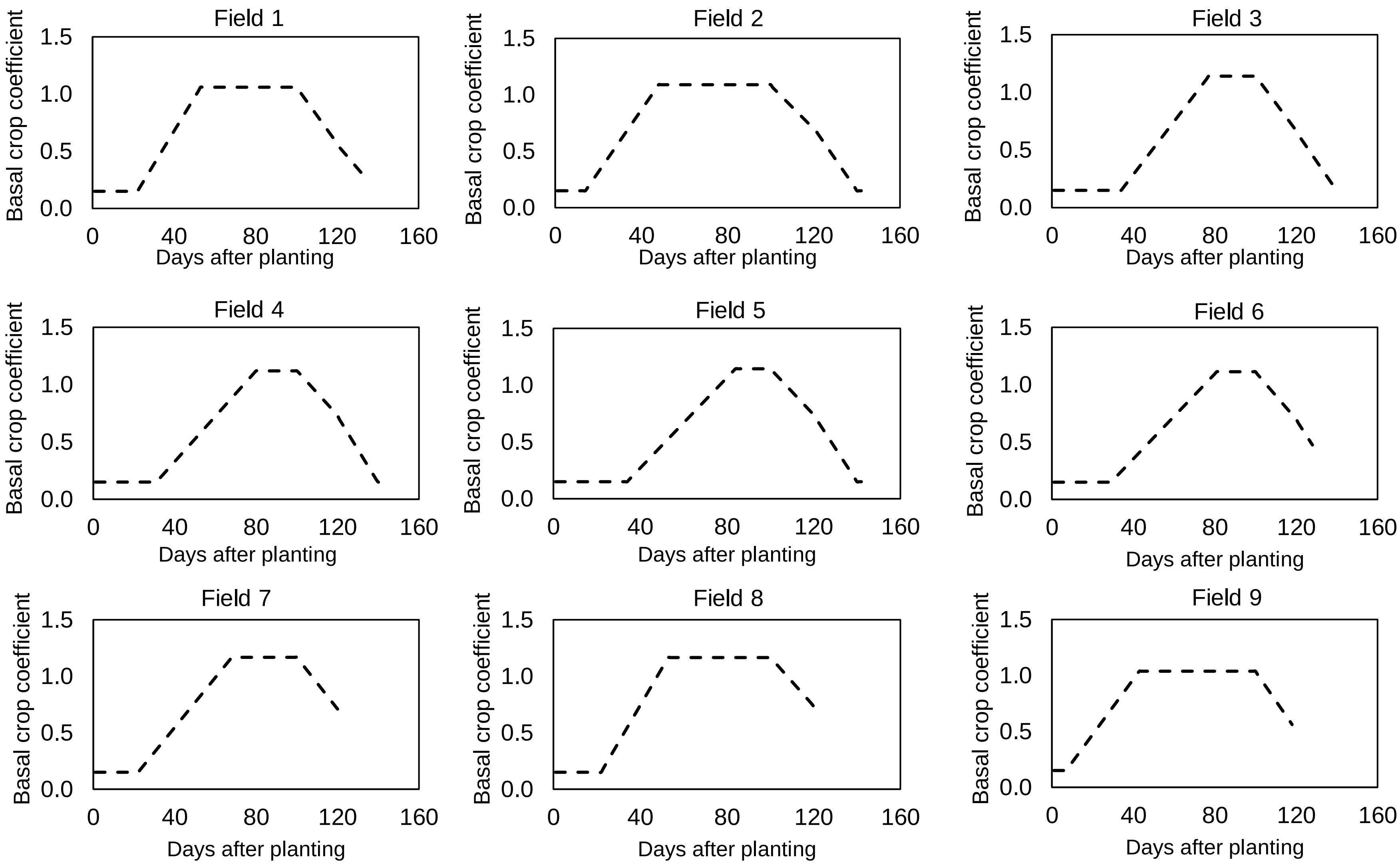

Figure 4.11. Basal crop coefficient curves calculated using FAO-56 adjusted Kcb(mid) and Kcb(end) values to meet the specific climatic conditions. The curves allow for the estimation of crop ET at various stages of crop growth.

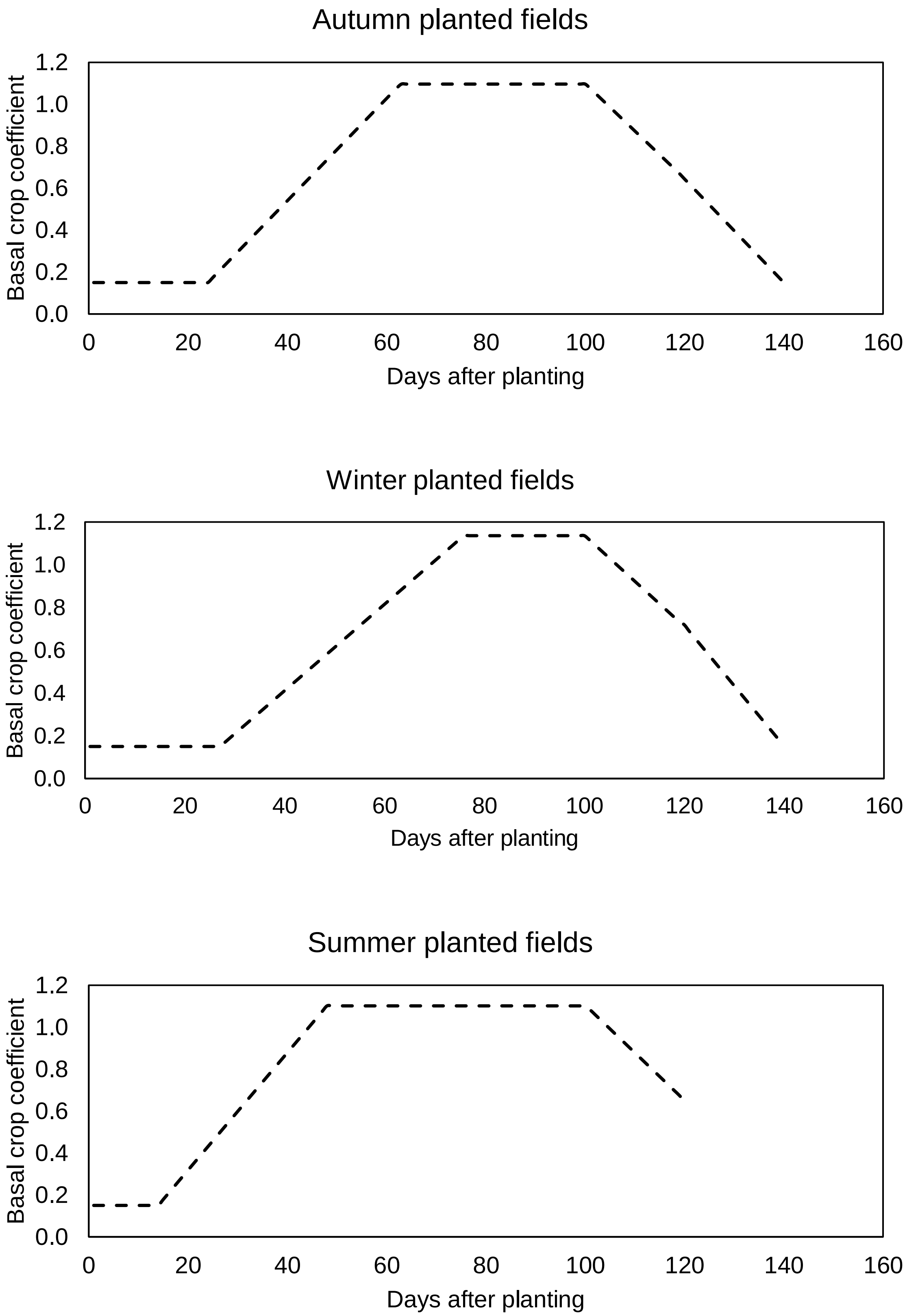

Figure 4.12. Proposed standardised basal crop coefficient curves to estimate ET for potato crops in the Sandveld region during different planting periods (autumn, winter and summer).

All Kcb(mid) and Kcb(end) (Table 4.4) values were adjusted to account for the impact of differences in aerodynamic roughness between the potato crop and reference grass crop as discussed by Pereira et al. (1999). Allen et al. (1998), Allen et al. (2011) and Allen and Pereira (2009) recommended Kcb(ini), Kcb(mid) and Kcb(end) values for the production of Kcb curves for potato crops. On average, Sandveld fields had a 3.7% higher adjusted Kcb(mid) value than that suggested by FAO-56 (Allen et al. 1998) for potato crops, with the exception of Field 1, which had a 3.7% lower adjusted Kcb(mid) value. The same was seen for Kcb(end), which had a 9.5% higher adjusted value. Fields 1 and 9, however, produced 13.1 and 13.7% lower Kcb(end) values, respectively. Overall, this suggests a general slight under-estimation when calculating ET using FAO-56 (Allen et al. 1998) values for the Sandveld region. Therefore, Sandveld Kcb values must be estimated regionally to ensure more accurate approximation of irrigation requirements, compared to the FAO reported values. The regional adjustment of Kcb values was also suggested by Gupta et al. (2017). The Kcb(mid) and Kcb(end) values obtained in this study are higher than those reported by Paredes et al. (2018), who calibrated the potential Kcb(mid) and Kcb(end) of potato crops in Italy (also a Mediterranean-type climate) and obtained values of 1.10 and 0.35, respectively. Sousa and Pereira (1999), likewise reported a value of 1.10 for Kcb(mid). The Kcb(mid) values obtained in the Sandveld were more in line with those reported by Trebejo and Midmore (1990) and Slatni et al. (2011) at 1.15 and 1.12, respectively. The Kcb values, however, represent mainly the transpiration component of ET and may have under-estimated seasonal ET demand, particularly during the early stages of crop development when more evaporation from the bare soil surface takes place (Rosa et al. 2012). It was reported for maize crops that the evaporative component of ET is 80% during the initial growth period, with an average of 41% throughout growth (Zhao et al. 2013). For wheat the average contribution of evaporation to total seasonal ET demand was reported at 30% (Zhang et al. 2003; Zhang et al. 2013a) and 26% (Kang et al. 2003). However, all studies indicated highest evaporative (E) contribution to ET demand during early crop stages. The over-simplification of the Kcb curve may, therefore, miscalculate potential ET (Mohktari et al. 2018). It is suggested that the dual crop coefficient is a more precise estimation when crops do not completely cover the soil surface, as the evaporation component will be estimated more accurately. However, the evaporative component is often difficult to calculate (Zhao et al. 2013).

Table 4.3. Duration (days) of each stage of the basal crop coefficient curve and the calculated mean for all autumn, winter and summer planted fields. The Kcb(ini) was used from planting to crop emergence; Kcb(mid) from the duration of 100% canopy cover and Kcb(end) at crop termination.

Field	Planting to emergence	Emergence to 100% canopy cover	Duration of 100% canopy cover	Start of senescence to crop termination
Field 1	21	31	47	35
Field 2	13	34	52	42
Field 3	33	43	23	40
Field 4	29	49	20	46
Field 5	33	50	16	42
Field 6	28	52	19	28
Field 7	21	46	32	20
Field 8	21	31	47	20
Field 9	6	36	57	18
Autumn	22	36	41	39
Winter	28	49	22	34
Summer	14	34	52	19

Table 4.4. Basal crop coefficient values adjusted to suit climatic conditions for the Sandveld region.

	Kcb(mid)	**Kcb(end)**
Max	1.17	0.74
Min	1.04	0.56
Mean	1.12	0.68
Autumn planted (mean)	1.10	0.64
Winter planted (mean)	1.14	0.72
Summer planted (mean)	1.10	0.65

The Kcb(ini) was not adjusted to climatic factors and remained 0.15.

Standardised Kcb curves were produced from the data obtained (Figure 4.12) and can potentially be used as a guideline for producers. Average length of planting to crop emergence and crop emergence to 100% canopy cover was determined for Autumn (March to June), Winter (end of June to July) and Summer (October to November) planted fields. Field 9 experienced lower temperatures than a typical summer grown field located in the Sandveld. The lower temperatures, due to its location close to the ocean, contributed to the underestimation of the standardised summer Kcb values.

4.2.2.2 Irrigation requirements

The Kcb curves allowed for the estimation of crop water use. The ET values calculated using the basal crop coefficient curve [ET(Kcb)], ET from the calculated soil water balance [ET(SWB)] and ET as calculated by the LINTUL DSS potato model [ET(LINTUL)] are illustrated in Table 4.5.

For most fields, the LINTUL model produced ET values much higher than those calculated using the Kcb curves (Fields 1 to 6). The difference in calculated water use ranged from 12.9 to 217.3 mm (Fields 2 and 3, respectively). Field 1, 2, 6, 8 and 9 differed between the two calculation methods by only ≤10%. The ET(SWB) for Field 3, 7 8 and 9 was closer to the ET(Kcb) than ET(LINTUL). The ET(SWB) values were high for all fields, with the exception of Field 3, where ET(SWB) was lower than calculated ET(LINTUL). The ET(SWB) calculations varied from ET(Kcb) and ET(LINTUL) for Field 3 by 64 and 153 mm respectively. The average deviation between ET(Kcb) and ET(SWB), for all fields, is 141 mm, whereas the average deviation between ET(LINTUL) and ET(SWB) is 161 mm.

Theoretically the total ET values over the season cannot exceed cumulative seasonal ET_o, due to Kcb values <1 for majority of the season. For Fields 2 and 5 the ET(SWB) exceeded the ET_o by far. The high values can potentially be attributed to the slopes of these two fields, as runoff was observed. However, runoff is not reflected in the SWB calculation, which probably contributed to the over estimation of ET. Thus, it can be assumed that the ET (Kcb) estimated slightly more representative water use values for the region.

Table 4.5. Evapotranspiration (mm) calculated using the LINTUL DSS potato model and basal crop coefficient curves calculated using weather parameters obtained from each field.

Field	ETo	ET(Kcb)	ET(SWB)	ET(LINTUL)
Field 1	320	188	-	210
Field 2	373	266	550	279
Field 3	310	195	259	412
Field 4	531	321	-	438
Field 5	558	346	628	450
Field 6	420	305	-	323
Field 7	543	478	568	403
Field 8	790	647	743	607
Field 9	392	368	405	341

Figures 4.13 to 4.21 indicate the simulated irrigation requirements according to calculated ET, taking into account system efficiencies. Irrigation requirement increases from winter to summer planted crops due to the conducive conditions for more rapid growth as well as higher temperatures and ET_o occurring. Winter planted crops required less water due to colder, wetter and cloudier climatic conditions. The first planted field, Field 1, had a total calculated ET(Kcb) of 188 mm. Irrigation application was low at 260 mm, which was 19% more than the simulated IR(Kcb) and only 9% higher than the simulated IR(LINTUL). When taking into account the leaching requirement to remove the build-up of excess salts (Table 4.7), then the total irrigation

application carried out by the farmer is only 5 mm more than the simulated water requirement [LR(LINTUL)] (Figure 4.13). However, throughout the season, from planting to harvest, irrigation application is on average 39% higher than the water requirement simulated from IR(LINTUL), including the LR and 43% higher throughout the season than the calculated IR(Kcb), including the LR. Field 2 (Figure 4.14) showed a similar trend to Field 1. However, Field 2's irrigation application was substantially higher throughout crop growth in comparison to the simulated Kcb and LINTUL irrigation requirements. The ET(Kcb) for Field 2 was 266 mm, with actual irrigation application being 486 mm. The actual application was 136 mm higher than the simulated IR(Kcb) and 119 mm higher than the simulated IR(LINTUL) (Figure 4.14). When taking into consideration the leaching requirement, the simulated irrigation requirement for the season was 371 mm and 389 mm (Kcb and LINTUL, respectively). This is 24% and 20% less than the actual irrigation application at the end of the season. For Field 3 (Figure 4.15) the crop was in the field for an extended period (174 days). During the early stages of crop development, IR(Kcb) is larger than the irrigation application (2nd May until the 13th June). This can be attributed to the commencing of irrigation only with crop emergence (4th June). However, the soil profile was irrigated prior to planting and hence, ET took place as the soil contained sufficient water until emergence. From the 13th June onwards the irrigation application exceeded the IR simulated by Kcb and LINTUL until October, when it dropped below the IR(LINTUL) again. The IR(Kcb) and cumulative irrigation application followed a similar trend for Field 3, although IR(Kcb) always remained lower than the actual irrigation application throughout the season. For this field, irrigation application was 27% less and 35% more than the IR(LINTUL) and IR(Kcb) respectively. When LR is considered, irrigation applied still differed from the required water application by 33 and 30% for IR(Kcb) and IR(LINTUL), respectively.

The fields planted end of June and early July (Fields 4, 5 and 6) had similar ET (Kcb) values, ranging from 305 to 346 mm for the season. Fields 4 and 5 had similar total water inputs (rainfall and irrigation) with total irrigation applications (562 and 545 mm, respectively) being 41 and 19% higher for Field 4 with regards to the simulated IR(Kcb) and IR(LINTUL) respectively. For Field 6 (Figure 4.18), on the other hand, the irrigation application and simulated water requirements followed the same trend until early September where after the simulated water requirements exceeded the actual irrigation application. Final simulated IR(Kcb) and IR(LINTUL) for Field 6 were 3.8 and 9.2% higher than the actual irrigation application, suggesting only slight under-irrigation. However, the soil profile contained a water table and hence LR was not required. The applied water was thus held in the soil profile for longer periods, particularly during colder conditions.

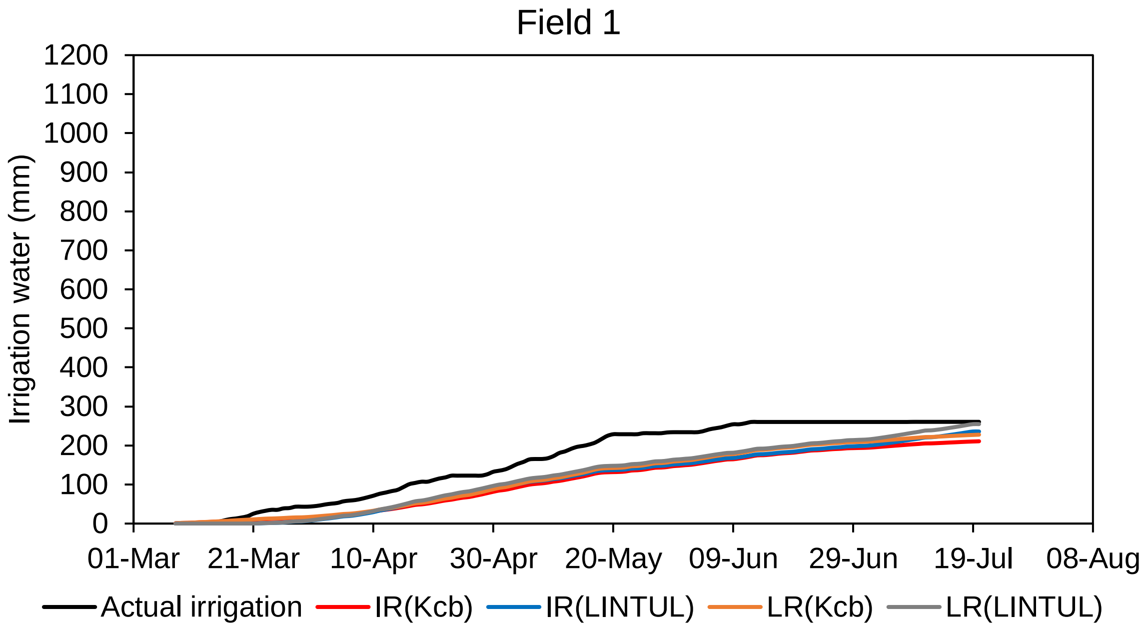

Figure 4.13. Cumulative irrigation requirements calculated using crop ET demands from the basal crop coefficient curve [IR(kcb)] and LINTUL potato model [IR(LINTUL)] compared to actual irrigation applied throughout the season. Leaching requirement is also calculated for each method.

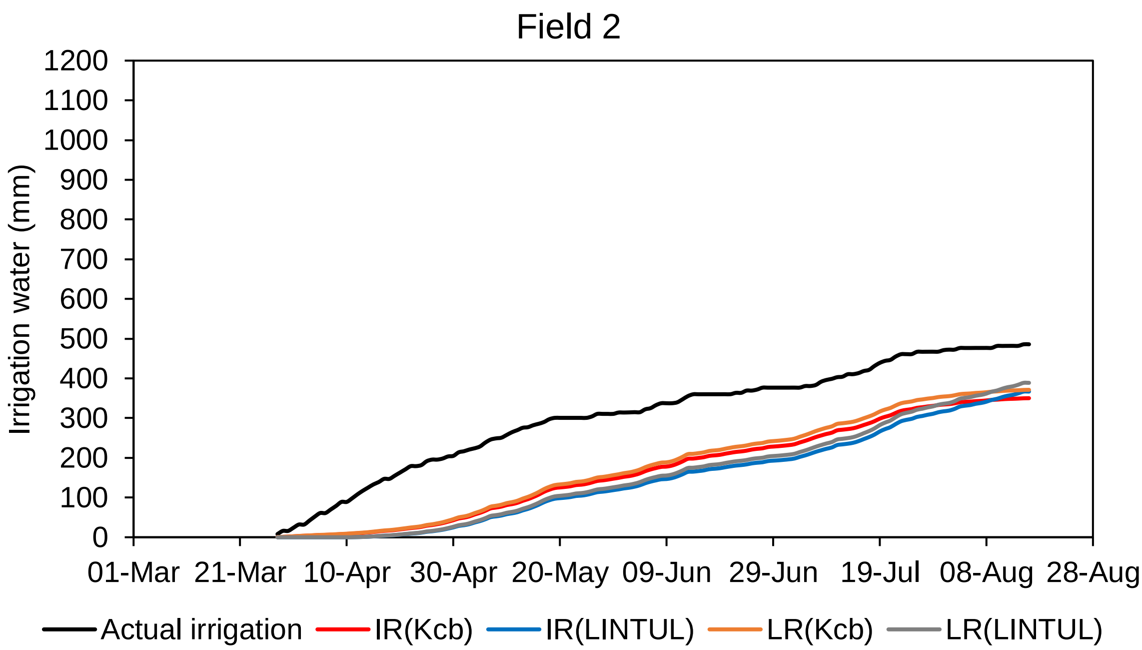

Figure 4.14. Cumulative irrigation requirements calculated using crop ET demands from the basal crop coefficient curve [IR(kcb)] and LINTUL potato model [IR(LINTUL)] compared to actual irrigation applied throughout the season. Leaching requirement is also calculated for each method.

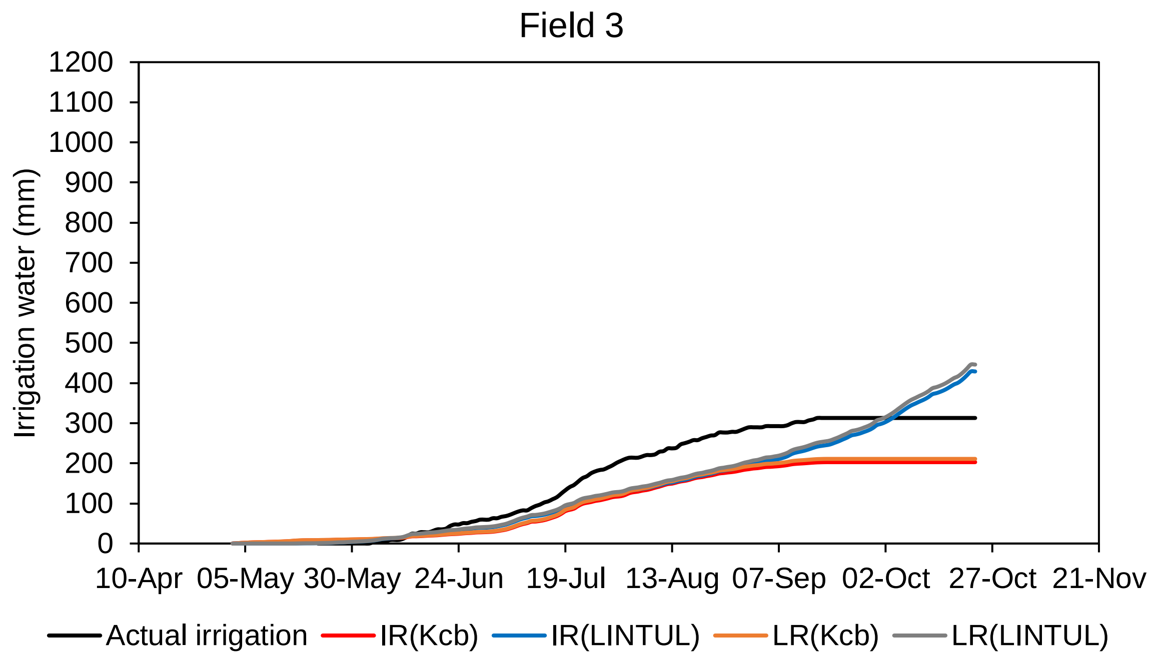

Figure 4.15. Cumulative irrigation requirements calculated using crop ET demands from the basal crop coefficient curve [IR(kcb)] and LINTUL potato model [IR(LINTUL)] compared to actual irrigation applied throughout the season. Leaching requirement is also calculated for each method.

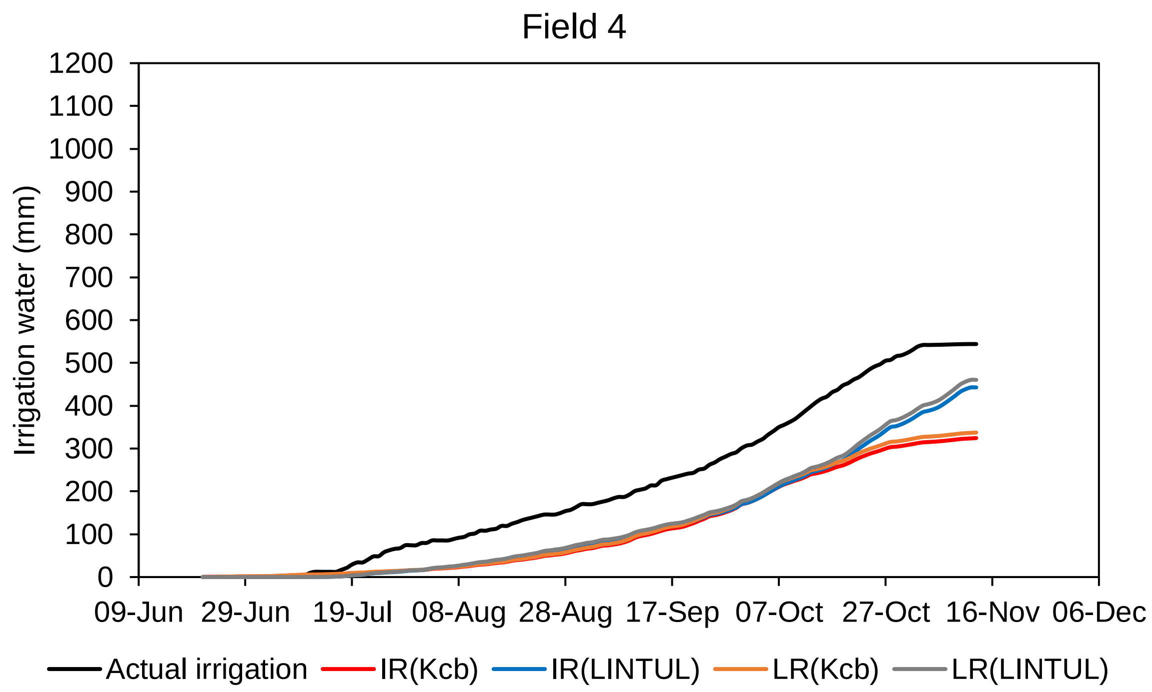

Figure 4.16. Cumulative irrigation requirements calculated using crop ET demands from the basal crop coefficient curve [IR(kcb)] and LINTUL potato model [IR(LINTUL)] compared to actual irrigation applied throughout the season. Leaching requirement is also calculated for each method.

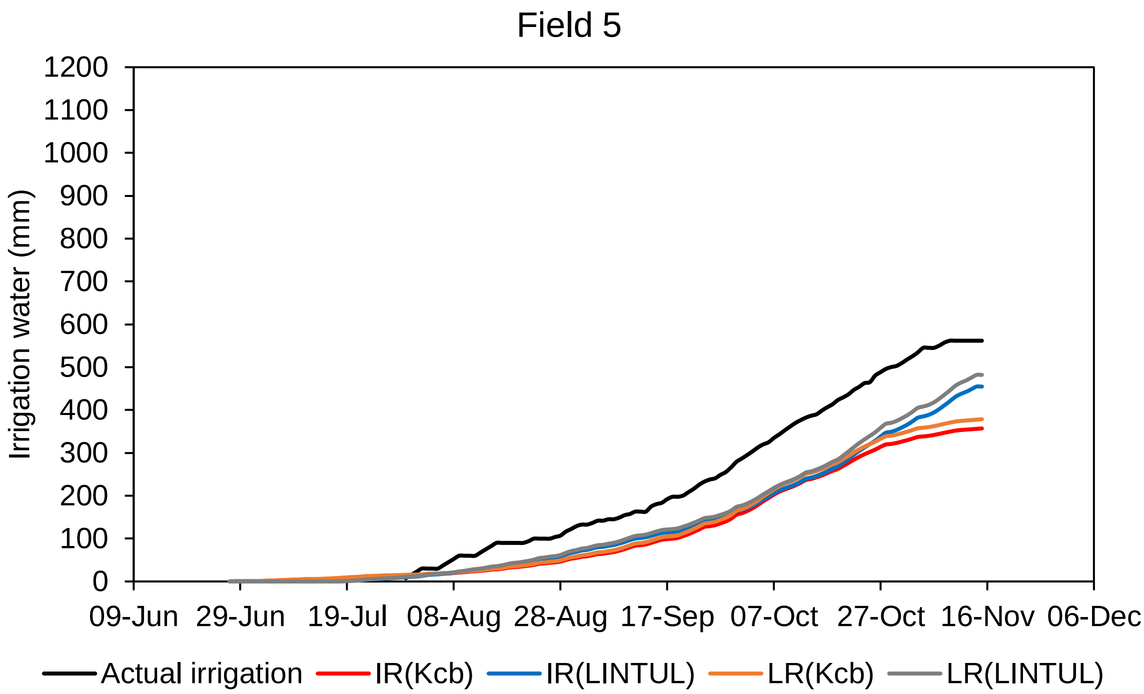

Figure 4.17. Cumulative irrigation requirements calculated using crop ET demands from the basal crop coefficient curve [IR(kcb)] and LINTUL potato model [IR(LINTUL)] compared to actual irrigation applied throughout the season. Leaching requirement is also calculated for each method.

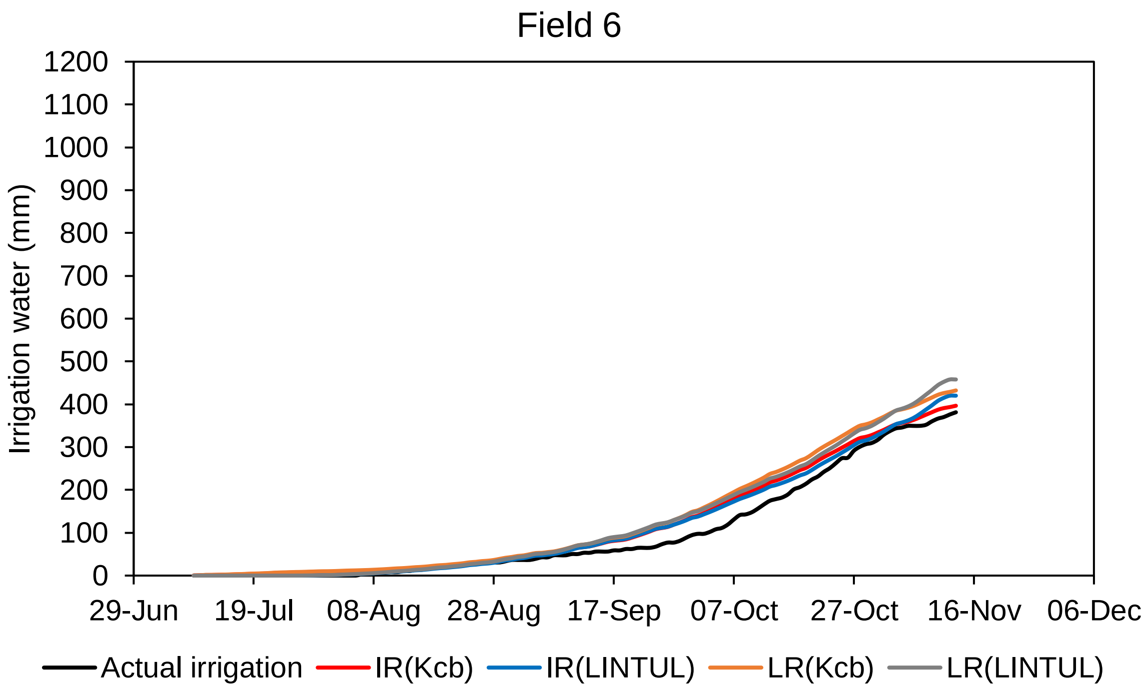

Figure 4.18. Cumulative irrigation requirements calculated using crop ET demands from the basal crop coefficient curve [IR(kcb)] and LINTUL potato model [IR(LINTUL)] compared to actual irrigation applied throughout the season. Leaching requirement is not necessary for this field due to the presence of a shallow clay layer, causing a water table.

Field 7 (Figure 4.19) showed similar irrigation application to simulated IR. The application of water was only slightly higher than the simulated IR until the end of October, whereafter it dropped below the IR(Kcb). The irrigation water used for this field was very saline (Table 4.7) and hence leaching may be required to prevent the build-up of salts. When the LR is taken into consideration then the IR(Kcb) and IR(LINTUL) where 18.5 and 3.5% higher than actual application. Therefore, it can be noted that only slight under irrigation occurred. It can be assumed that under-irrigation occurred during the middle of the season and onwards, as irrigation exceeded the calculated ET during the early stages of crop development. Field 8 had very large simulated water requirements for IR(Kcb) and IR(LINTUL) (1011 and 949 mm, respectively). The simulated irrigation requirement, due to Field 8's low AE (64%), increased disproportionally, resulting in very high estimated irrigation needs. Irrigation application was 9.7 and 3.8% less than the simulated requirement. The simulated IR compared to actual application goes up to of 13.2 and 7.5% (IR(Kcb) and IR(LINTUL), respectively) when LR is taken into consideration. For Field 9 the irrigation requirement was underestimated due to missing weather data during the early crop period (30th November to 20th December).

For all curves, IR(Kcb) followed a similar trend to the actual irrigation applied, with curves levelling off towards the end of the season, whereas ET(LINTUL) produced constantly increasing simulated IR. Differences of 10% and under between simulated water requirements and irrigation application show good agreement. The LINTUL DSS potato model estimates crop physiology according to growth degree-days. Crop emergence was calculated by LINTUL using a sprout growth rate of 0.7 mm per degree-day above 0 °C, therefore, the emergence date as calculated by LINTUL DSS varied from that visually noted for the Kcb curves. However, for both LINTUL and the Kcb curves, the duration (days) from emergence to 100% canopy cover was calculated with the same assumption. This was estimated using the value reported by Haverkort et al. (2015) of 650-degree days from crop emergence to full canopy cover. Where the two methods differ substantially is in the calculation of ET. The LINTUL DSS model uses a dual crop coefficient approach, estimating both ET and bare soil evaporation. LINTUL DSS uses a set Kcb(mid) value of 1.1, which is not adjusted for Sandveld climatic conditions. The Kcb values for both Kcb(mid) and Kcb(end) were adjusted when using the Kcb curves. The bare soil evaporation component is calculated as 1/3 of the daily ET_o for LINTUL DSS, however, for Kcb curves the evaporation component was excluded and the calculation made primarily on the transpiration component. The soil cover estimated by LINTUL DSS is calculated using the assumption that maximum soil cover is reached at a LAI of 3. Thereafter, soil cover is assumed to remain 100% until haulm killing. However, if the crop naturally dies off, the model makes an error. It has been shown from Eddy covariance measurements that ET shows a declining trend in the second half of the growing season. As leaves senesce, ET declines irrespective of weather conditions (Personal Communication, AC. Franke; unpublished data).

Given that ET was not measured directly in the Sandveld, it cannot be stated which method was more accurate as both depend on a set of assumptions. However, the use of the ET(SWB) gives us an independent estimate of ET, which indicates different values to those obtained by the Kcb curve and LINTUL DSS potato model.

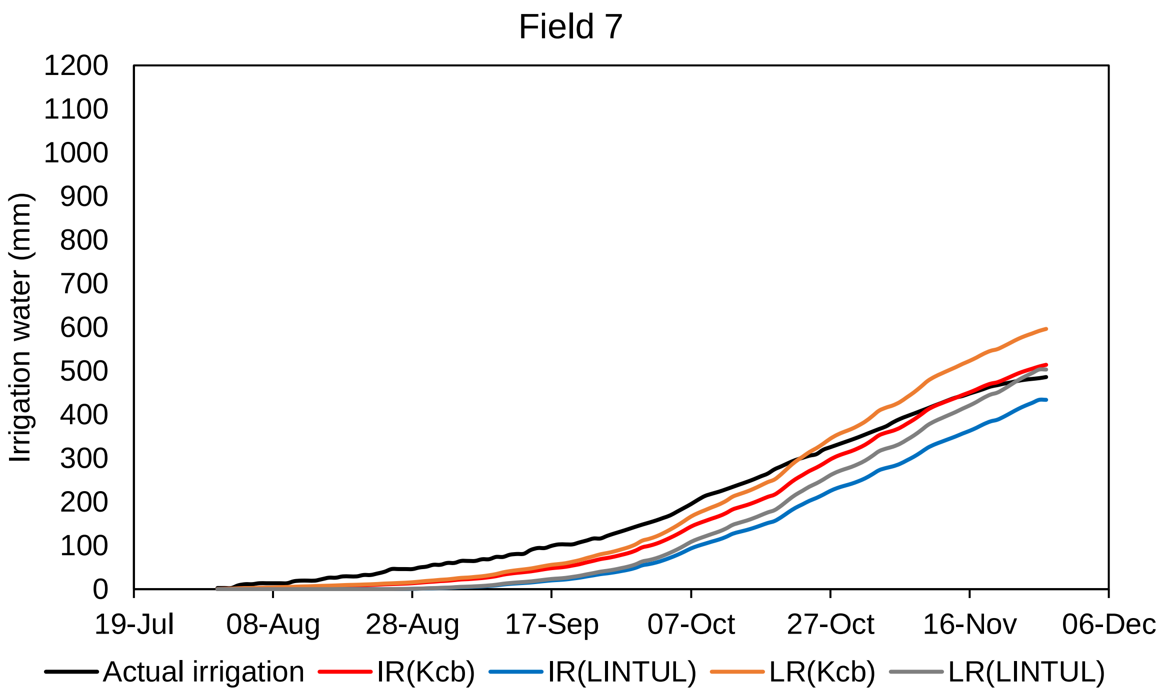

Figure 4.19. Cumulative irrigation requirements calculated using crop ET demands from the basal crop coefficient curve [IR(kcb)] and LINTUL potato model [IR(LINTUL)] compared to actual irrigation applied throughout the season. Leaching requirement is also calculated for each method.

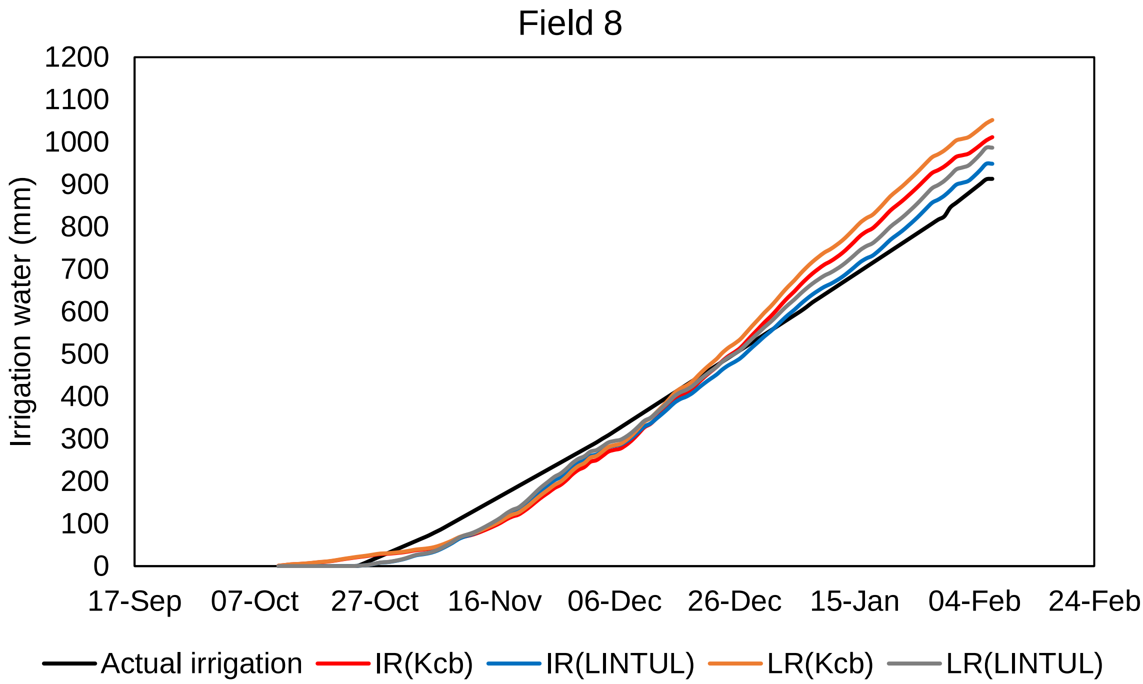

Figure 4.20. Cumulative irrigation requirements calculated using crop ET demands from the basal crop coefficient curve [IR(kcb)] and LINTUL potato model [IR(LINTUL)] compared to actual irrigation applied throughout the season. Leaching requirement is also calculated for each method.

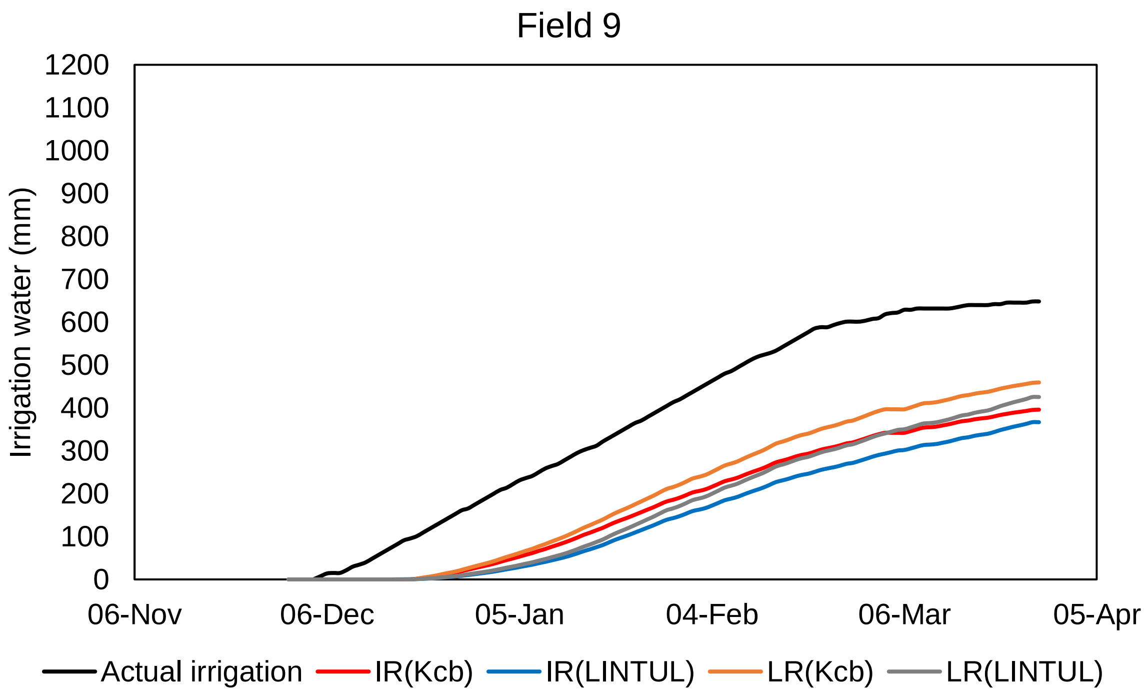

Figure 4.21. Cumulative irrigation requirements calculated using crop ET demands from the basal crop coefficient curve [IR(kcb)] and LINTUL potato model [IR(LINTUL)] compared to actual irrigation applied throughout the season. Leaching requirement is also calculated for each method.

4.2.3 Irrigation water quality

The threshold level of irrigation water for potato growth is considered 170 mS m^{-1} (Fertasa 2016). This value is the maximum permissible conductivity allowed without yield loss occurring. Producers generally believe that the water sources for irrigation in the area are slightly saline. Both the SAR and EC of the irrigation water used on each field was determined to acknowledge the salinity hazard of the irrigation water applied (Table 4.6, Figure 4.22) in order to determine whether a percentage of leaching and drainage was required.

Table 4.6. The sodium and salinity hazard classes for irrigation water. The sodium hazard classes are calculated using the sodium absorption ratio. The EC is well correlated with the dissolved salt content of water (Fertasa 2016).

Hazard class	Value	Description
Sodium Hazard		
S1	<10 mmol dm^{-3}	Suitable irrigation water, provided there is a low salinity hazard
S2	10 – 18 mmol dm^{-3}	Good irrigation water for use on well-drained sandy soils. The addition of gypsum is advisable on sandy soils. If applied on clay soils salinity will increase over time.
S3	18 – 26 mmol dm^{-3}	Use only with good management practices on well-drained soils. Unsuitable on soils with poor drainage.
S4	>26 mmol dm^{-3}	Unsuitable for irrigation water
Salinity Hazard		
C1	<25 mS m^{-1}	No salinity hazard
C2	25 – 75 mS m^{-1}	Avoid saline sensitive crops and ensure a reasonable degree of leaching is practiced
C3	75 – 225 mS m^{-1}	Use salt resistant crops and ensure periodic leaching is practiced. Only recommended on well-drained soils.
C4	>225 mS m^{-1}	Unsuitable for irrigation water. Under extreme conditions can be applied on sandy soils.

The class of analysed water sources ranged from C2:S1 to C4:S1 (Table 4.7). The recommended leaching requirement for each field with the acceptable yield reduction of 10% is relatively low for the region in most cases and ranged from 0.04 to 0.27 (Table 4.7). However, due to the crop rotation in the area (one-year cropping, four to six years fallow) the need for leaching of salts is low to negligible as there is potentially not a substantial build-up of salts in the soil. The ceasing of irrigation and only rainfall events occurring in fallow periods will result in the leaching of salts out of the effective rooting zone for potato crops. This is in agreement with Vaughan and Letey (2015), whose study indicated that crops grown under irrigation with saline water produced greater yields when seasonal rainfall occurred. The rainfall caused excess salts to leach to greater depths in the soil profile. It was also shown that factors that potentially reduce yield such as high saline conditions contributed to the increase in N leaching. Shalhevet (1994) reported that in well-drained soils under irrigation, system inefficiencies caused adequate leaching of excess salts. However, due to the long rotation periods in potato cropping systems and the relatively low leaching requirements observed for most of the fields monitored (Table 4.7), the leaching of salts should not be prioritised in potato production systems in the Sandveld, as it was not observed to be an issue in the area under normal field conditions.

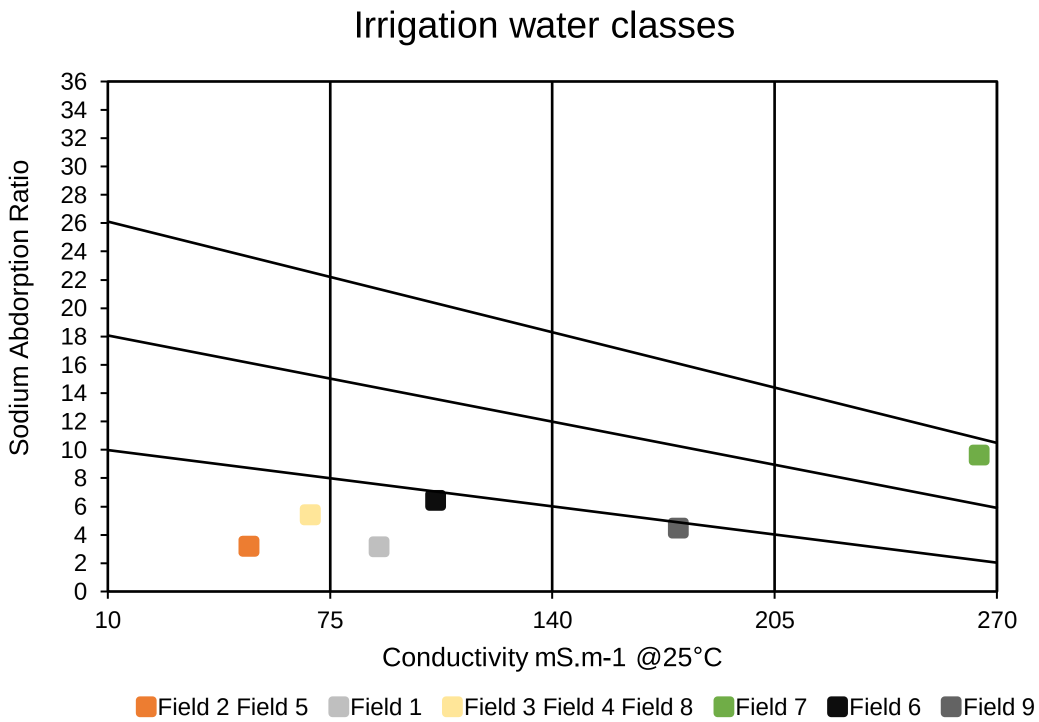

Figure 4.22. Water classes from irrigation sources based on EC and SAR. The markers represent the irrigation water class for the different fields.

Table 4.7. Quality parameters for the different irrigation water sources. Salinity hazard class is determined based on the SAR and the electrical conductivity.

Water Source	Field	EC_{IW} (mS m^{-1})	SAR (Ratio)	Class	Leaching Requirement (ratio)
1	2 and 5	51	3.1	*C2S1	0.04
2	3, 4 and 8	69	5.4	*C2S1	0.06
4	1	90	3.1	*C3S1	0.08
5	9	177	4.4	*C3S1	0.16
6	6	106	6.4	*C3S1	0.09
7	7	265	9.6	*C4S1	0.27

*refer to Table 4.6.

4.2.4 Soil water content

Data from DFM capacitance probes, which were installed in each field directly after planting, are represented in Figures 4.23 to 4.27. The DFM probes give relative soil water content values (scale 0 – 100) and not absolute soil water contents (fraction of percentage soil water). These sensors generally gave a good indication of changes in soil water contents over the growing season. In Figure 4.23 the periods of very wet conditions correspond with the deep drainage collected, due to substantial rain from late May to early July (compare with Figure 4.3), can clearly be observed for Field 2. In the example for Field 7 (Figure 4.24), the slightly dry subsoil and gradual increase in water content thereof can be noted. The two distinguished increases in soil water content observed (Figure 4.24, for 18 September and 23 October) both occurred after large water inputs through rainfall and irrigation. Field 5, which was grown during a similar time of year to Field 7, showed a very different tendency. The stepwise increase and decrease in soil water content can be viewed more easily as illustrated by Figure 4.25 (16 September to 4 November). The cause of this was due to very little rain occurring from the end of September to harvest. October was in general a hotter and drier month in the region as illustrated by the high daily ET (refer to Figure 4.6) and therefore, there was an increased frequency in soil water fluctuations due to the rapid depletion of profile water through wetting and drying. This stepwise wetting and drying clearly indicates the irrigation management of the field. The peaks above the upper readily available water limit shown for the root zone (0 to 50 cm) and top roots (0 to 20 cm) occurred at dips in daily ET and coincided with drainage accumulation. For Field 3, (Figure 4.26, compare with Figure 4.4) during the beginning of June there was a dip in daily ET and rainfall events occurring and hence, the incline in water contents observed for the root zone and top root zones. This coincided with the start of drainage collection from the 20th of June until the 4th of July, when conditions for this field were cold, cloudy and large amounts of rainfall occurred, causing an increase in drainage accumulation. The spikes in water content (1 July, 15 July, 7 August and 25 August) are in accord with the increase in drainage accumulation happening after large rainfall events and is a trend seen throughout Figures 4.23 to 4.27. The decline in water content viewed from the start of July to the middle of July in all zones for Field 3 (root zone (0 to 50 cm), top roots (0 to 20 cm) and buffer zone (60 cm) was attributed to a decrease in rainfall, low irrigation amounts and frequency as well as an increase in ET rate. Water input through rainfall and irrigation as well as ET directly affect drainage accumulation, which in turn influences the soil water content fluctuations.

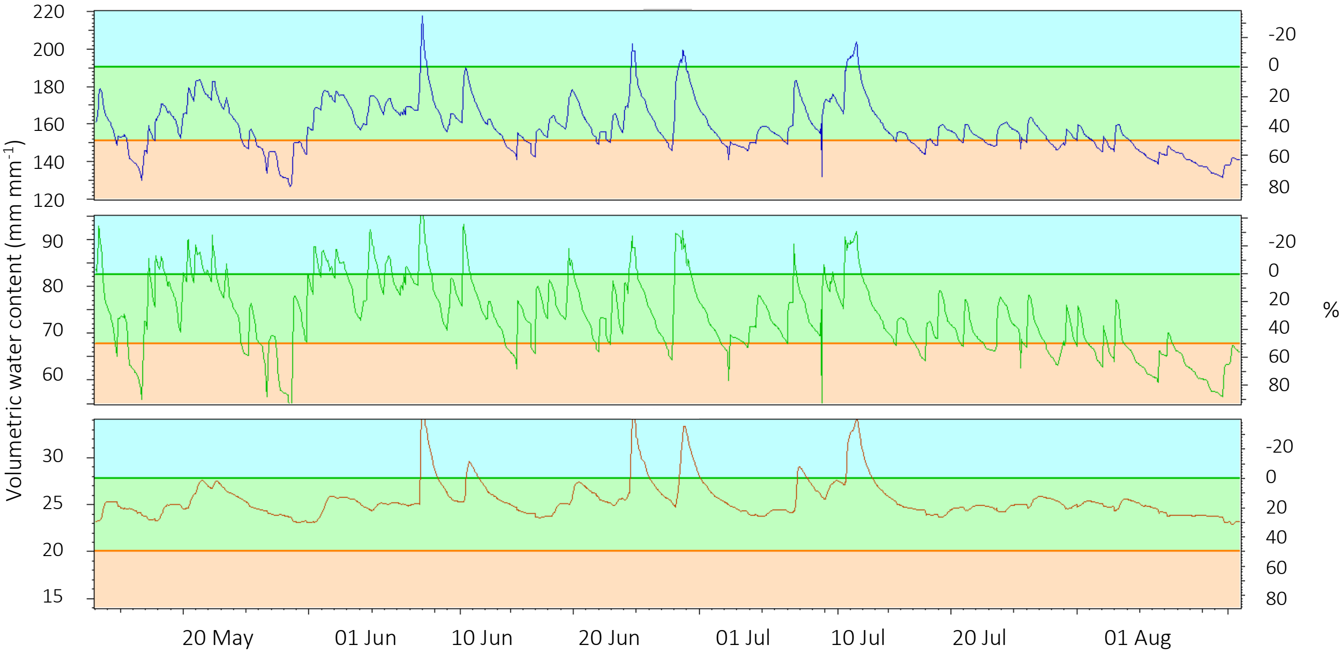

Figure 4.23. DFM capacitance probe measurements of soil water contents in the root zone (top), top roots (middle) and buffer zone (bottom) of Field 2.

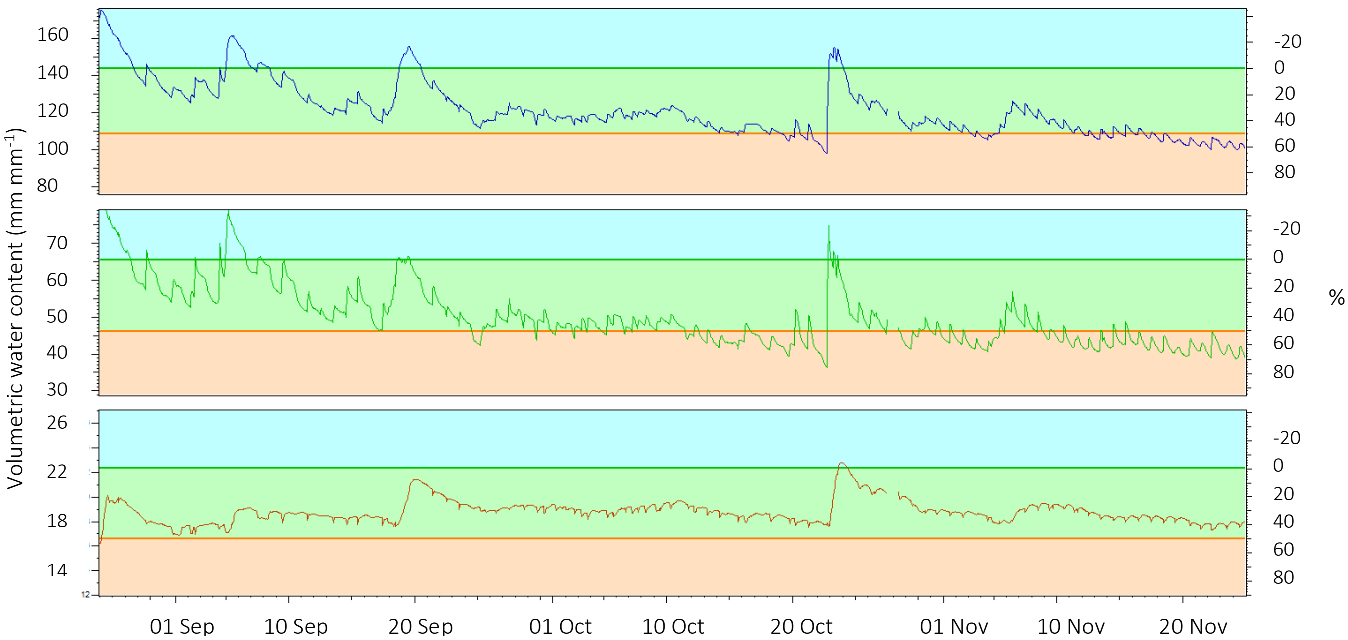

Figure 4.24. DFM capacitance probe measurements of soil water contents in the root zone (top), top roots (middle) and buffer zone (bottom) of Field 7 in the Sandveld.

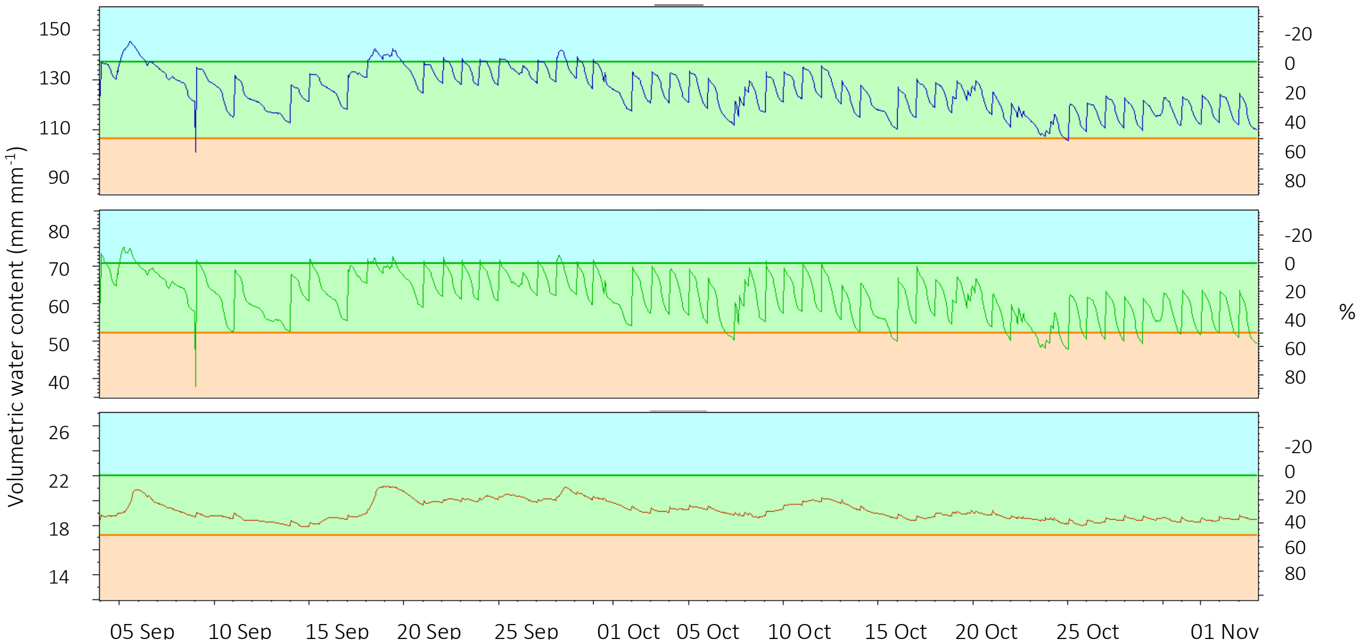

Figure 4.25. DFM capacitance probe measurements of soil water contents in the root zone (top), top roots (middle) and buffer zone (bottom) of Field 5 in the Sandveld.

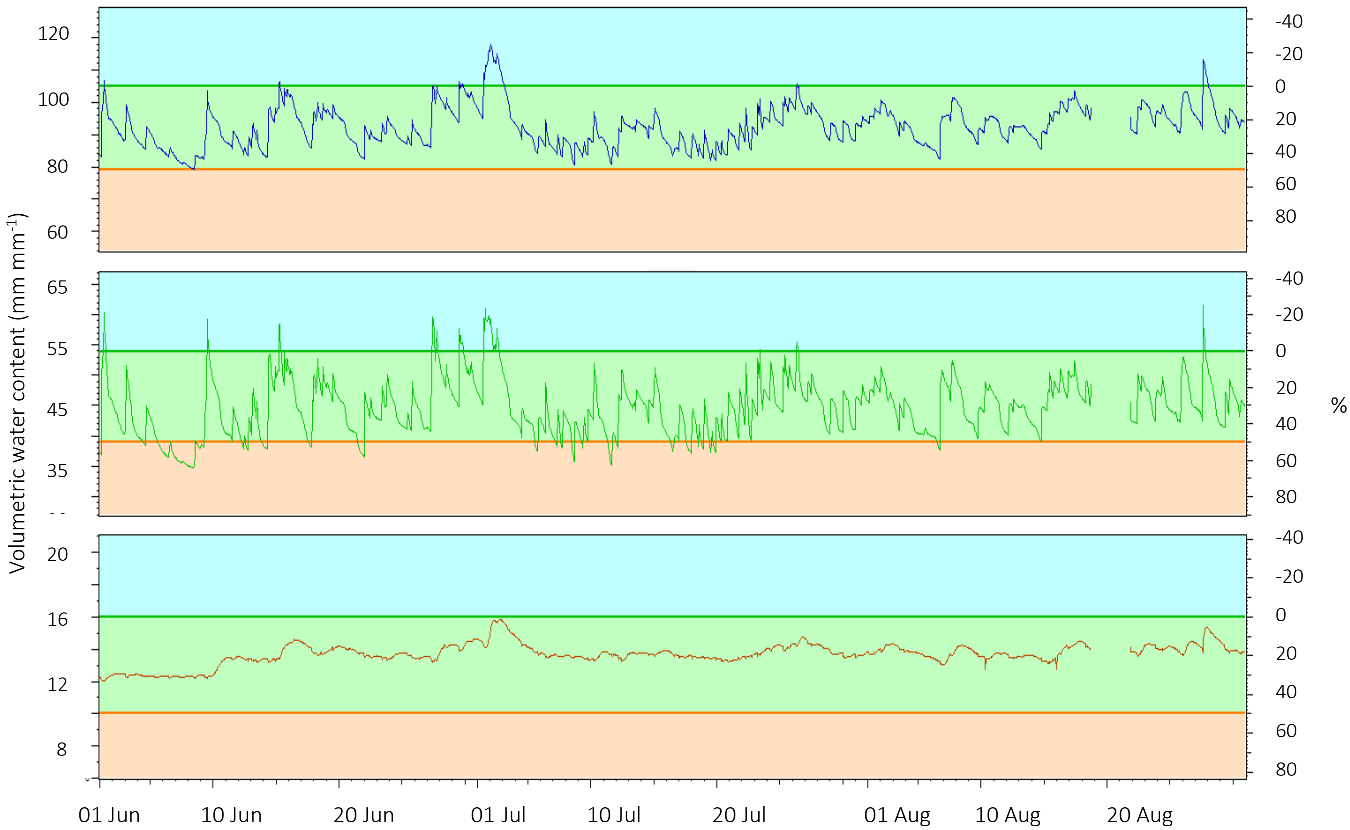

Figure 4.26 DFM capacitance probe measurements of soil water contents in the root zone (top), top roots (middle) and buffer zone (bottom) of Field 3 in the Sandveld.

Data collection by DFM probes linked with telemetry was generally seamless, except in places where cell phone reception was unreliable. This was especially problematic for some of the fields due to the mountainous topography surrounding fields. As a result, for some of the fields, data from only one probe, or in some cases no data, could be retrieved from those farms. This was the case for various fields, but is clearly demonstrated by the graphical representation of soil water content throughout the season for Field 9 (Figure 4.27).

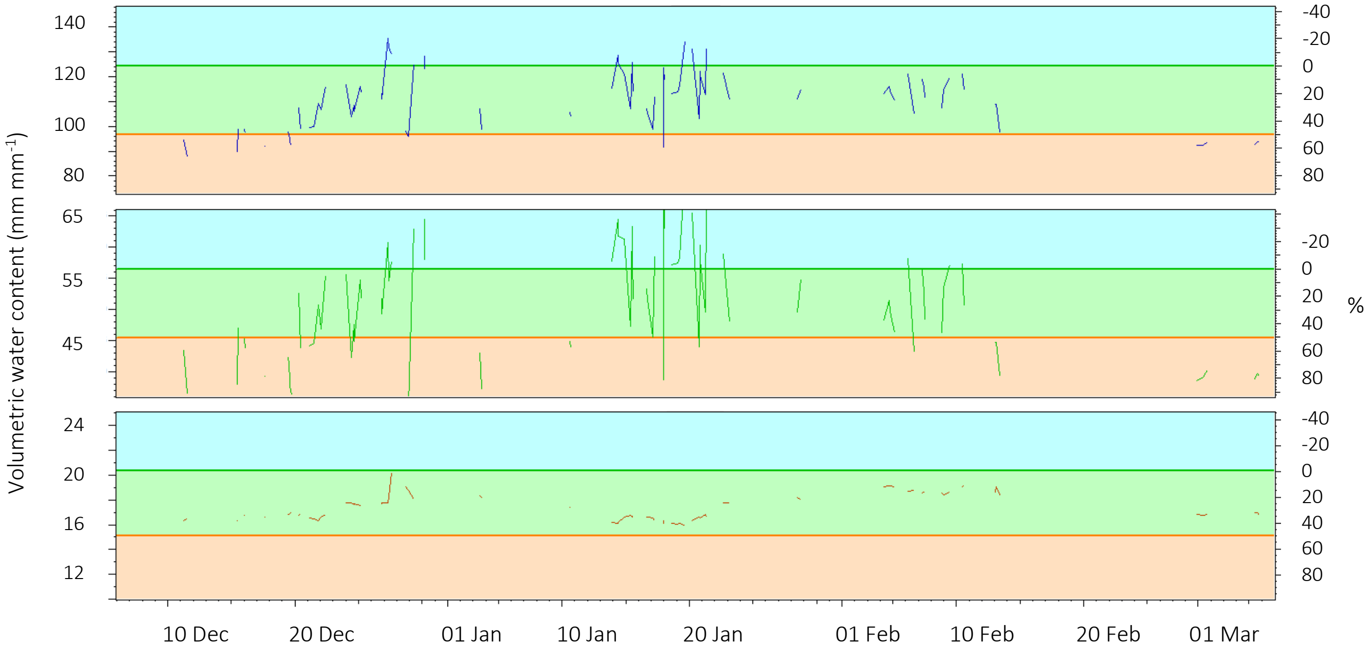

Figure 4.27. DFM capacitance probe measurements of soil water contents in the root zone (top), top roots (middle) and buffer zone (bottom) of Field 9 in the Sandveld. Data collection was incomplete due to poor cellular reception and the partial and sporadic collection of data throughout the growing season as illustrated by the incomplete soil water content lines.

The Decagon sensors showed a similar trend to the DFM probes. However, some data points are missing for various sensors and periods in certain monitored fields (Figures 4.28 to 4.33) due to logger problems or dysfunctional sensors. Decagon (volumetric water content) values were lower than those given by the DFM probes. When compared to random gravimetric sampling (data not presented) Decagon values were closer and more accurate, however, the use of soil water monitoring tools in this study was not aimed at obtaining actual soil water content data, but to observe the fluctuation in profile water with drainage accumulation.

During this study, producers did not have access to the capacitance probe data and, therefore, did not manage irrigation scheduling accordingly. However, it is believed that these probes can be valuable irrigation scheduling tools in order to decrease drainage and optimise irrigation management. Fields 8 and 9 had battery failure over December, resulting in missing data points. However, a general decreasing trend in soil water content (%) during the period of no data collection was observed.

The Chameleon soil water potential sensors, which were also evaluated at the intensively monitored fields in the Sandveld, unfortunately gave poor response in the very sandy soils present. The sensors inserted into the east section of Field 3 showed very different soil water movement to the readings given by the sensors inserted into the west end of the field. The east sensor results indicated a lower soil water potential than the west, for the depth of 25 cm and 50 cm (green and red colours). This does slightly coincide with the DFM data for that section; however, conditions were not very dry during the early part of the season as suggested by the Chameleon data. In the case of Field 7, Chameleon data suggested saturated conditions throughout the entire season, which does not follow the observed soil water content trends from the DFM or Decagon probes. The DFM and Decagon probes illustrate a drier soil profile during the early cropping season and an increase in soil water content towards harvest. Field 2 showed a similar trend. The result is that the colour patterns mainly remained blue, (Figure 4.34 to 36) suggesting that the soils were consistently very wet, which does not agree with the DFM or Decagon data. Therefore, these sensors cannot supply producers with useful information to make good management decisions in the Sandveld region, due to the nature of the soil texture. The reason for the constant readings of field saturation is due to the inability of the Chameleon sensors to equilibrate with the sandy textured soils because of the sudden drop in unsaturated hydraulic conductivity when these soils dry out rapidly.

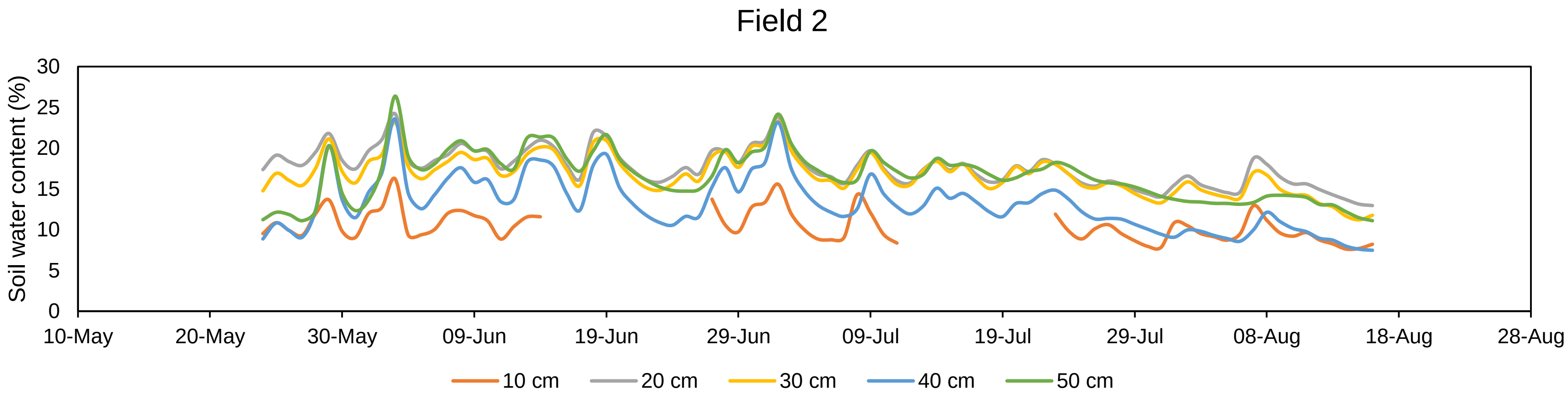

Figure 4.28. Field 2 Decagon capacitance probe soil water content data from a depth of 0-50 cm at 10 cm intervals. The missing data at 10 cm depth is due to sensor malfunctioning.

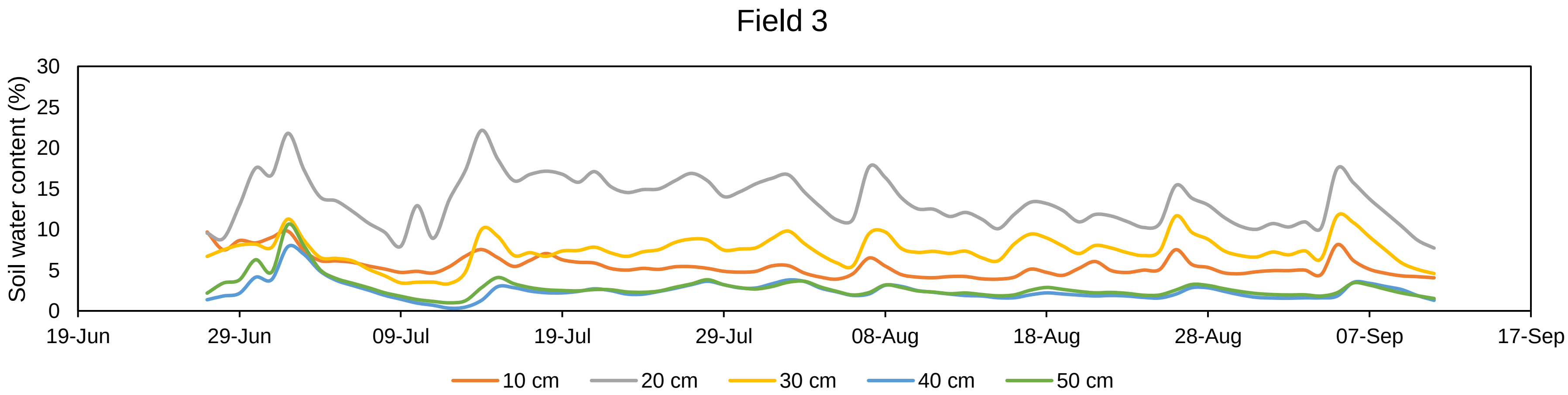

Figure 4.29. Field 3 Decagon capacitance probe soil water content data from a depth of 0-50 cm at 10 cm intervals.

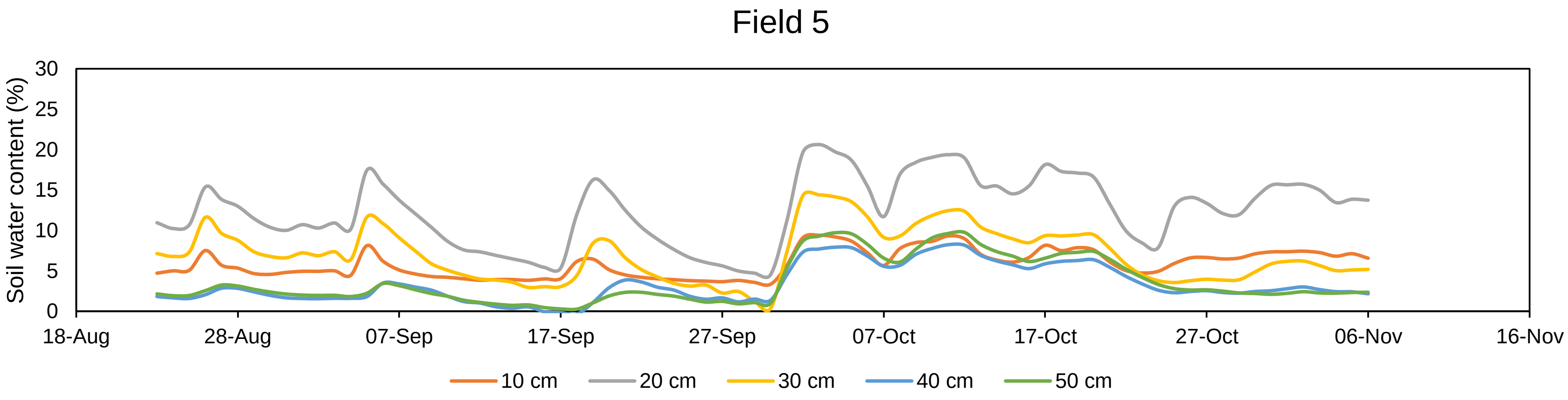

Figure 4.30. Field 5 Decagon capacitance probe data from a depth of 0-50 cm at 10 cm intervals.

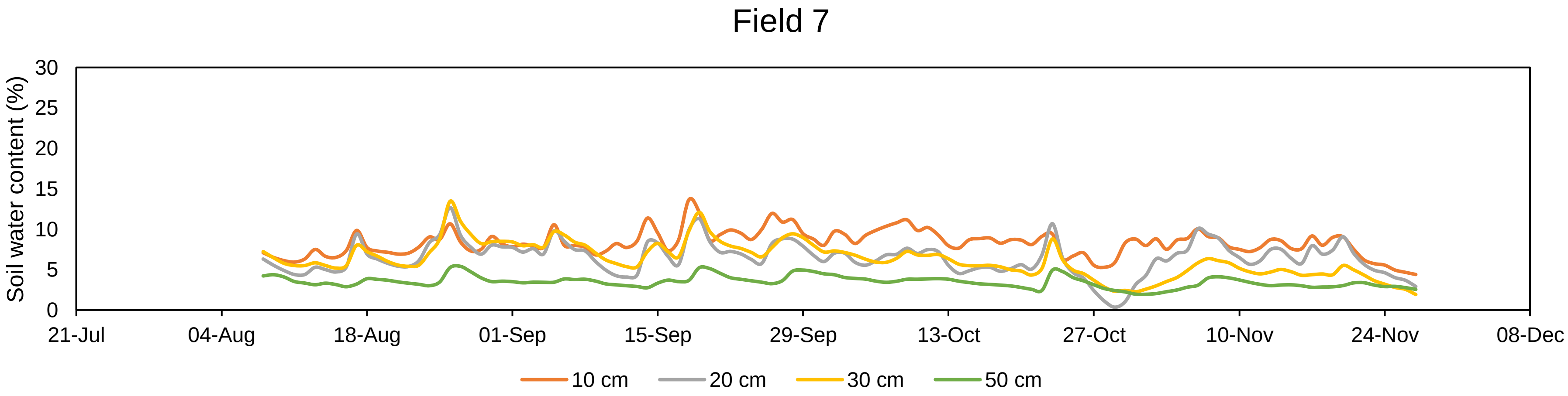

Figure 4.31. Field 7 Decagon capacitance probe data from 0-50 cm depth excluding the 40 cm depth due to a faulty probe.

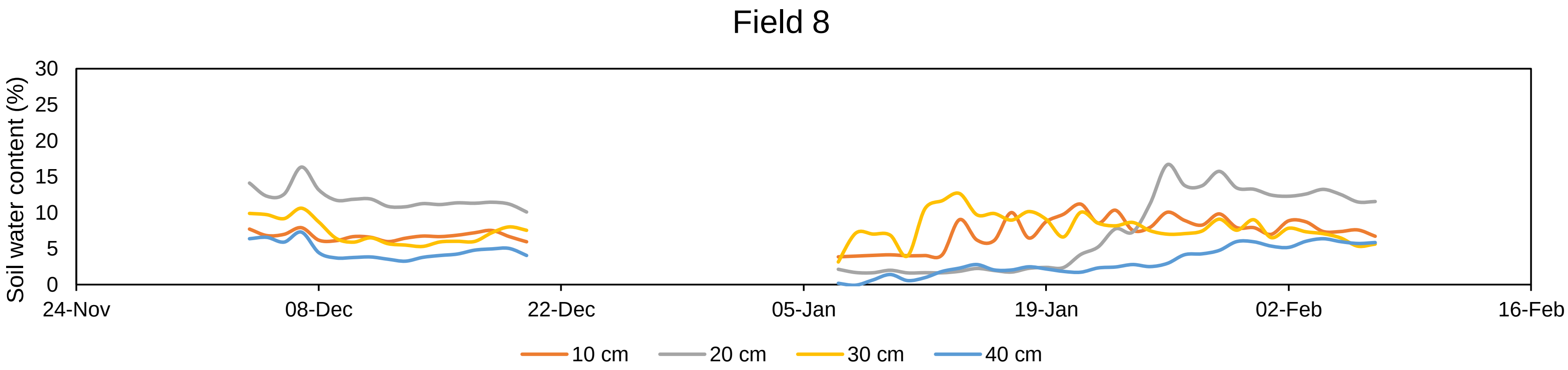

Figure 4.32. Field 8 Decagon capacitance probe data from a depth of 0-40 cm at 10 cm intervals. 50 cm probe data is missing due to a faulty sensor. Gap in data was due to battery failure.

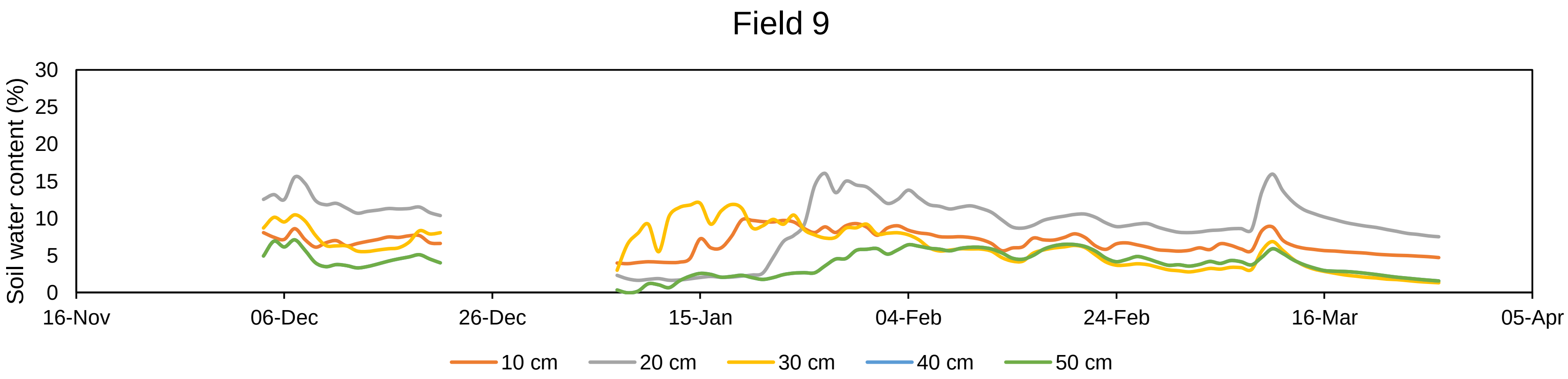

Figure 4.33. Field 9 Decagon capacitance probe data from a depth of 0-40 cm, with readings at 10 cm intervals. 50 cm probe data missing due to a faulty sensor. Gap in data was due to battery failure.

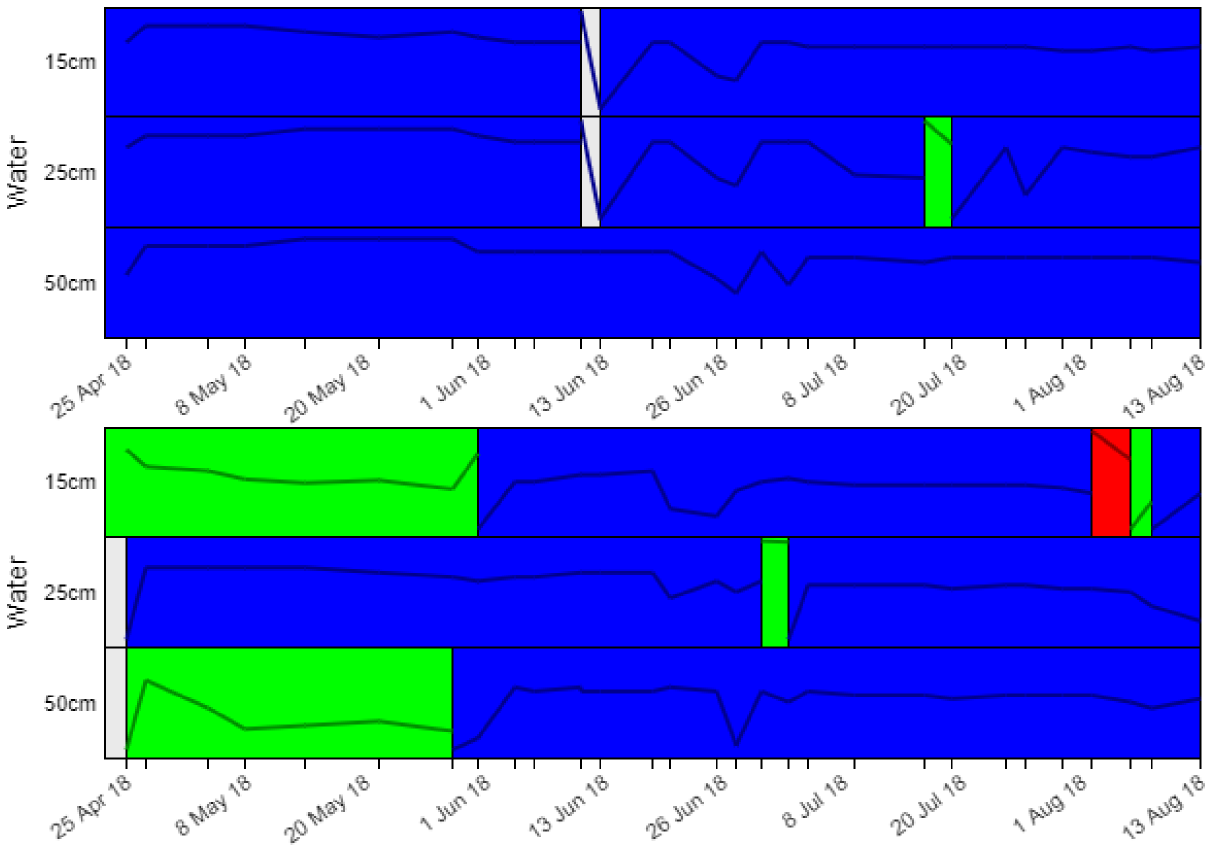

Figure 4.34. Chameleon probe data for Field 2, (top) west inserted probe and (bottom) east inserted probe. The colours red, blue and green represent a tension of >50 kPa, 20–50 kPa and 0–20 kPa, respectively. A tension of 0 kPa indicates a soil that is saturated and >50 kPa represents a dry soil. Lines indicate the link between logger reading taken throughout the season.

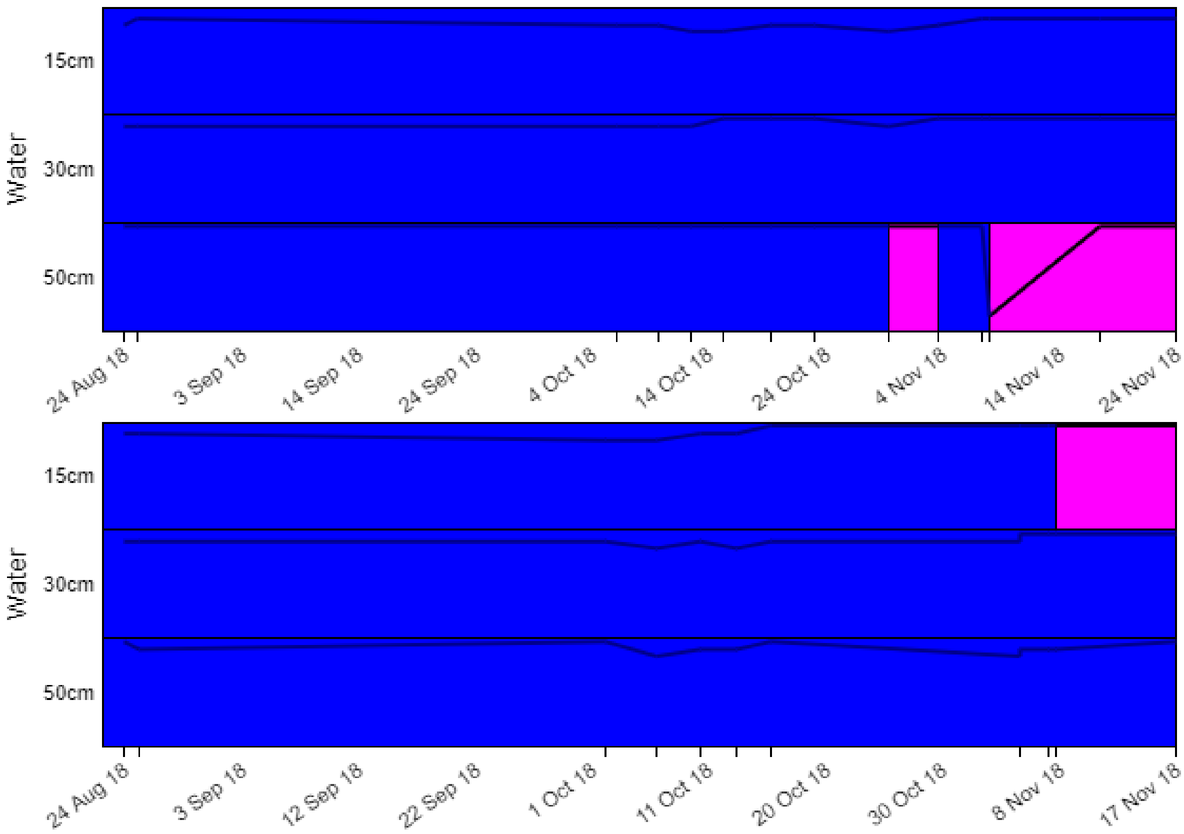

Figure 4.35. Chameleon probe data for Field 7, (top) probe inserted in the east section of the field, (bottom) probe inserted into the west side of the field. The colours red, blue and green represent a tension of >50 kPa, 20–50 kPa and 0–20 kPa, respectively. A tension of 0 kPa indicates a soil that is saturated and >50 kPa represents a dry soil. Lines indicate the link between logger reading taken throughout the season.

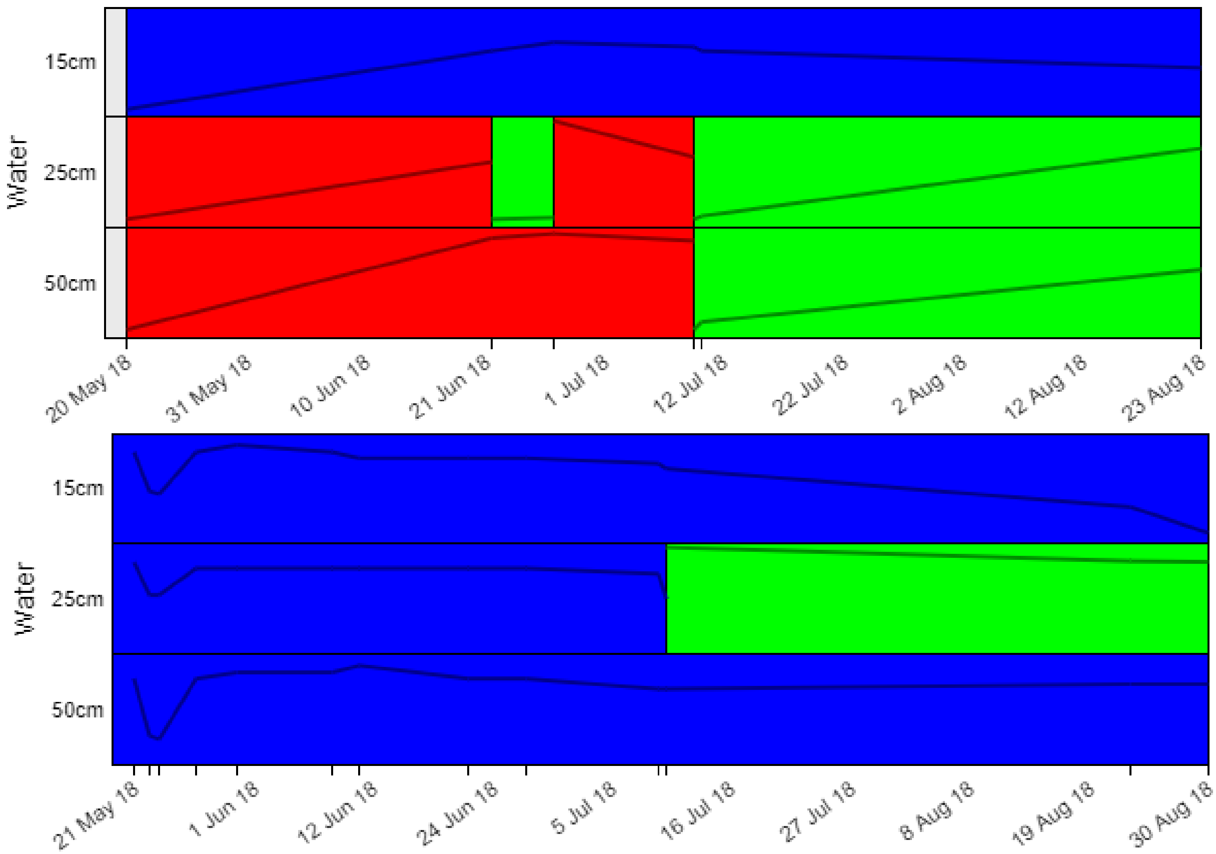

Figure 4.36. Chameleon probe data for Field 3. Top is the east-side, bottom is the West side. The colours red, blue and green represent a tension of >50 kPa, 20–50 kPa and 0–20 kPa, respectively. A tension of 0 kPa indicates a soil that is saturated and >50 kPa represents a dry soil. Lines indicate the link between logger reading taken throughout the season.

4.2.5 Water use efficiency

Water use efficiencies, calculated using yield and total water input by rainfall and irrigation (Ali et al. 2016), ranged from 65.4 (Field 1) to 122.2 kg mm^{-1} (Field 8) with an average of 85 kg mm^{-1} (Table 4.8). The average WUE falls above the acceptable WUE of 75 to 80 kg mm^{-1} as reported by Steyn et al. (2016). The average WUE of winter plantings was 79.5 kg mm^{-1}. Four out of the nine fields did not achieve WUE values above the acceptable norm. These low WUE values can be ascribed to a combination of factors. During winter months, the yield potential of potatoes is generally lower due to less available solar radiation, although in some cases other factors (e.g. disease occurrence and seed problems) resulted in the low yields. Large winter rainfall events also resulted in substantial unproductive water losses through drainage (or runoff) for some of the fields, resulting in low WUE. All four of the fields with lower WUE (75 to 80 kg mm^{-1}) received substantial rainfall (143 – 271 mm) during the crop growing season, which added considerably to the total amount of water these crops received, and affected the WUE negatively. Results obtained in this study were much lower than those reported in a Mediterranean climate in Italy by Katerji and Mastrorilli (2009) for clay (161 kg mm^{-1}) and loam (210 kg mm^{-1}) soils. The values reported by Katerji and Mastrorilli (2009) were, however, calculated using yield and estimated crop ET. Higher results however, can be anticipated in clay and loam soils as the sandy soils present in the Sandveld, have lower water holding abilities. Sandveld producers can also not be expected to leave substantial room for rainfall in the soil profile due to low water holding capacities, as this could result in water stress and yield losses, should a sudden hot spell occur.

When excluding the effect of rainfall in the calculation of WUE and referring to IWUE (Darwish et al. 2006; El-Abedin et al. 2017) results show a higher efficiency ranging from 89 to 134 kg mm^{-1}, which are higher than those reported by Darwish et al. (2006). Darwish et al. (2006) reported IWUE ranging from 0.80 to 1.06 kg DM m^{-3} (equivalent to 40 – 53 kg mm^{-1}, if a DM content of 20% is assumed), in a dry Mediterranean climate located in Bekaa, Lebanon. Ahmadi et al. (2014) reported IWUE values of 173 and184 kg mm^{-1} for the cultivars Ramos and Agria, respectively, in Shiraz, Iran where the climate is warm with an average annual rainfall of 386 mm. The average IWUE of 113.2 kg mm^{-1} obtained in the Sandveld is less than the lower range indicated by Ahmadi et al. (2014) on silty-clay loam soils for the variety Ramos. The WUE and IWUE generally decreased with an increase in water supply, which is in agreement with other reports in the literature (Fabeiro et al. 2001; Kashyap and Panda 2003; Yuan et al. 2003; Darwish et al. 2006; Ierna et al. 2011; Ierna and Mauromicale 2012). Ierna and Mauromicale (2012) stated the ability to reduce irrigation amounts by 77 mm year^{-1} when irrigating at 100% of the maximum ET from tuber initiation to 50% of the tuber growth only, whilst still obtaining high IWUE and tuber quality, indicating the importance of altering irrigation management according to crop phase.

Table 4.8. Water use efficiency and IWUE obtained within the Sandveld region. Calculated was the potential WUE and IR using outputs provided by LINTUL POTATO DSS model and the ratio between actual irrigation application (AI) and IR as estimated using the Kcb curves

Field	WUE (kg mm^{-1})	IWUE (kg mm^{-1})	*Potential WUE (kg mm^{-1})	**AI:IR(Kcb)
Field 1	65.4	133.4	87.0	1.23
Field 2	69.3	106.1	62.6	1.39
Field 3	76.2	132.6	141.5	1.54
Field 4	82.0	105.5	103.0	1.68
Field 5	70.7	88.6	95.3	1.57
Field 6	95.7	134.3	100.7	0.96
Field 7	96.7	111.0	104.1	0.95
Field 8	122.2	129.4	92.4	0.90
Field 9	86.2	91.0	131.4	0.63

*calculated from the potential yield given by the LINTUL POTATO DSS model and irrigation and rainfall applied to the fields.
** Ratio of actual irrigation (AI) to the irrigation requirement calculated by the Kcb curve.

4.2.6 Nutrient leaching

It is evident that nutrient leaching is substantial and may be attributed to the high levels of rainfall or irrigation received, following the same trend as drainage accumulation. To illustrate this, more leaching was obtained from Field 3 (Figure 4.37) early in the season, particularly during the sprouting and vegetative period, followed by a decrease in nutrient leaching throughout crop growth. Large rainfall events occurred during the month of June, coinciding with early crop development, whereafter rainfall occurrences decreased, the plant roots developed deeper and plant nutritional requirements increased. From the second to the third sampling date (27 June to 9 July) the leaching and loss of nutrients below the root zone for N, P and K was 19, 27.8 and 24.2 kg ha^{-1}, respectively. The applied fertiliser on Field 3 during the fourth week after crop emergence (Appendix I), which was prior to the second leachate sampling date, was slightly higher for N and K than the previous weeks at 27 kg N ha^{-1}, 24.5 kg K ha^{-1}. However, the amount of P applied between weeks three and four after crop emergence, was similar to prior applications. The increase in leaching can be accredited to high rainfall events and due to this, irrigation frequency was reduced. A total amount of 58.4 mm rainfall and irrigation occurred at this time. The drop in irrigation resulted in the decreased leachate accumulation for Na, S, Mg and Ca, which are present in the irrigation water sources (Table 4.9) at relatively high concentrations (1.01 kg Na ha^{-1} mm^{-1}, 0.04 kg S ha^{-1} mm^{-1}, 0.13 kg Mg ha^{-1} mm^{-1} and 0.05 kg Ca ha^{-1} mm^{-1}). After this point, nutrient leaching decreased, following a similar trend as the decrease in drainage water collected (Figure 4.38).

Table 4.9. Chemical composition of the different irrigation water sources. Fields 2 and 5 shared the same water source, as well as Fields 3, 4 and 8.

Field	**pH**	**Total-N**	**P**	**K**	**Ca**	**Mg**	**S**	**Na**
		mg L^{-1}						
Field 1	7.2	4.37	0.09	1.37	34.4	22.0	10.9	95.5
Field 2	7.8	6.07	0.31	1.83	3.8	7.1	2.0	45.0
Field 3	7.2	0.00	1.13	1.34	5.2	12.9	4.4	100.6
Field 4	7.2	0.00	1.13	1.34	5.2	12.9	4.4	100.6
Field 5	7.8	6.07	0.31	1.83	3.8	7.1	2.0	45.0
Field 6	6.7	0.00	<0.75	<10	12.2	15.8	6.1	143.6
Field 7	7.7	0.00	<0.75	<10	36.6	48.0	18.5	375.8
Field 8	7.2	0.00	1.13	1.34	5.2	12.9	4.4	100.6
Field 9	4.3	7.86	<0.75	12.34	43.8	61.9	115.5	194.4

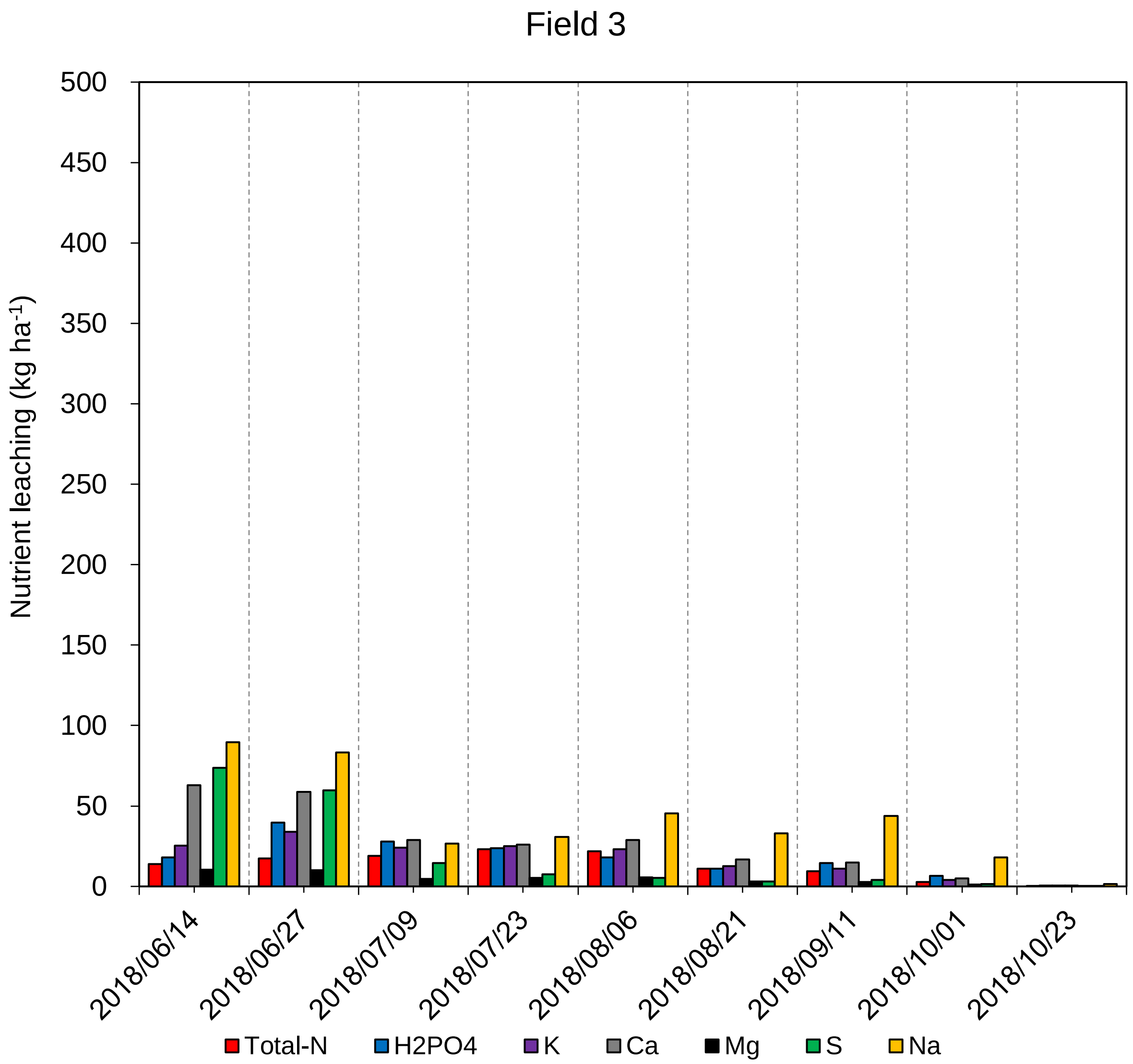

Figure 4.37. Nutrient leaching from Field 3 as measured from drainage solution collected fortnightly from the drainage lysimeter.

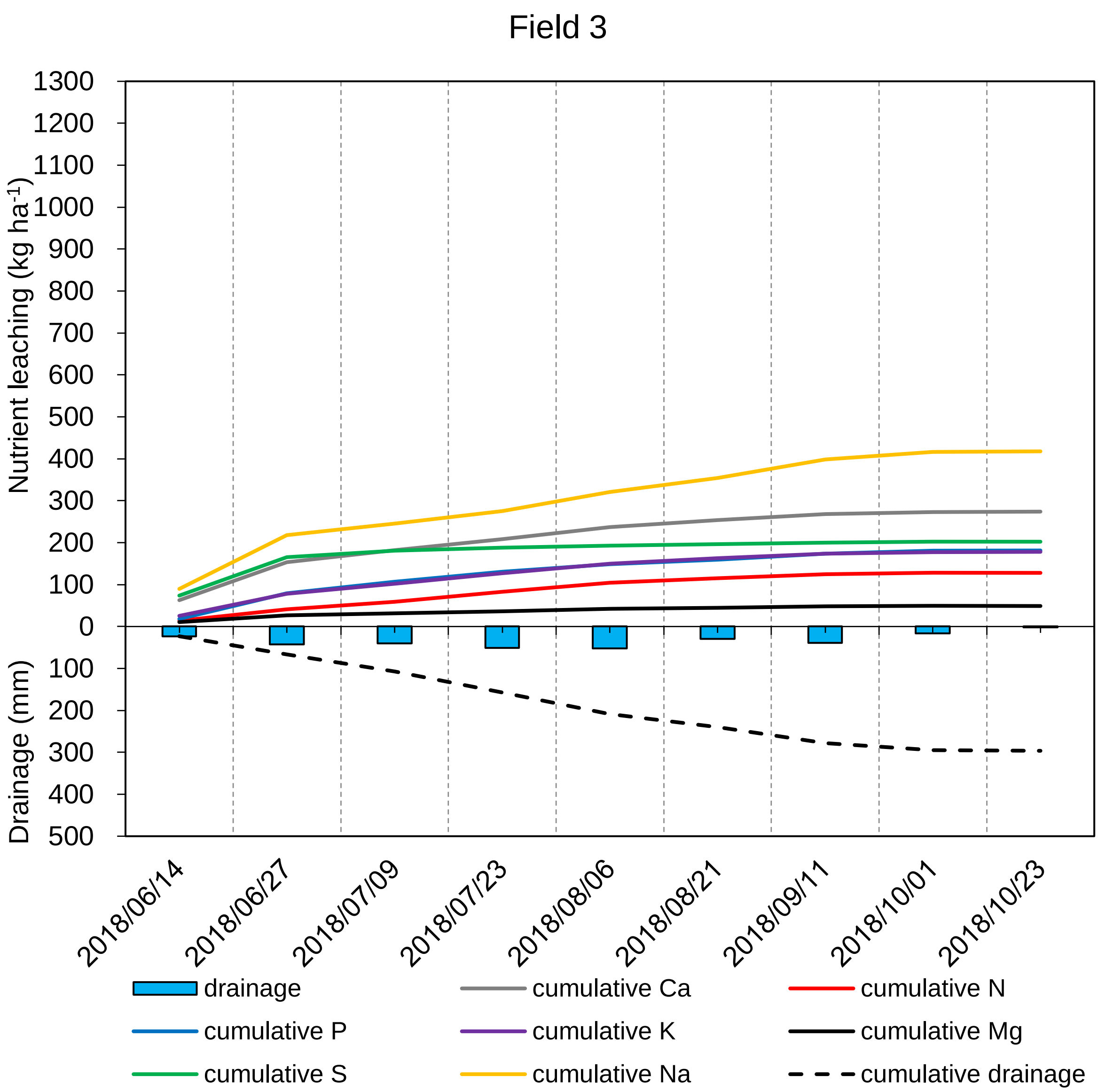

Figure 4.38. Cumulative macronutrient leaching compared to drainage collected for Field 3.

Field 2 (Figure 4.39) shows a different trend than Field 3, with nutrient leaching low during the first soil solution collection and increasing during the second collection. However, the explanation remains the same and is a tendency that is seen in all fields where drainage was collected. The spikes in nutrient leaching coincided with major water applications to fields through rainfall or when large amounts of irrigation were applied. Nutrient leaching for Field 2 (Figures 4.39 and 4.40) at the first sampling date (22 May) was generally low with 13.5 kg N ha^{-1}, 6.42 kg P ha^{-1}, 25.3 kg K ha^{-1}. The reason being that March, April and May 2018 were hotter and drier months with less rainfall. Hence, there was larger water movement out of the soil profile due to ET and less movement of nutrients downwards. Between sampling dates one and two

(2 May to 14 June) the field received 106 mm of rainfall, with a large rainfall event occurring on the 28th of May (34.2 mm). Within this period, there was 12 irrigation cycles applying a total of 71.2 mm, resulting in a total of 177.2 mm water being applied to the field. After the second sampling date, rainfall and irrigation application gradually decreased, resulting in less drainage (Figure 4.40). The total nutrients leached for the season from Field 2 was higher than that of Field 3 for K, Ca, Mg, S nutrients, however, 296 mm of soil solution drained from Field 3, compared to 205 mm in Field 2. The higher Mg and S leaching for Field 2 was not attributed to additions from irrigation water, as Mg and S concentrations in the irrigation water were lower (0.07 kg Mg ha^{-1} mm^{-1} and 0.02 kg S ha^{-1} mm^{-1}) than for Field 3. Only 5 kg ha^{-1} more Mg and 2 kg ha^{-1} more S fertiliser were applied to Field 2 than Field 3. However, the fertiliser regime for Field 2 used seven products containing S, applied over 13 applications (pre-planting up until week three). In comparison, Field 3 used four products containing S, all applied prior to crop emergence. The spreading of fertiliser application and higher water input (refer to Table 4.2 and Figures 4.3) during the early crop development on Field 2 may have attributed to the higher leaching of S. The explanation for the higher Mg leaching that occurred in Field 2 is most likely a result of the presence of more Mg in the soil profile (0 – 90 cm), as illustrated by the soil analysis (Appendix II).

Field 5 (Figures 4.41 and 4.42) followed the same leaching trend (advanced leaching with larger drainage accumulation), however, less nutrients leached throughout the cropping period compared to the other monitored fields. This is a result of less drainage occurring (only 74 mm in total) throughout the season.

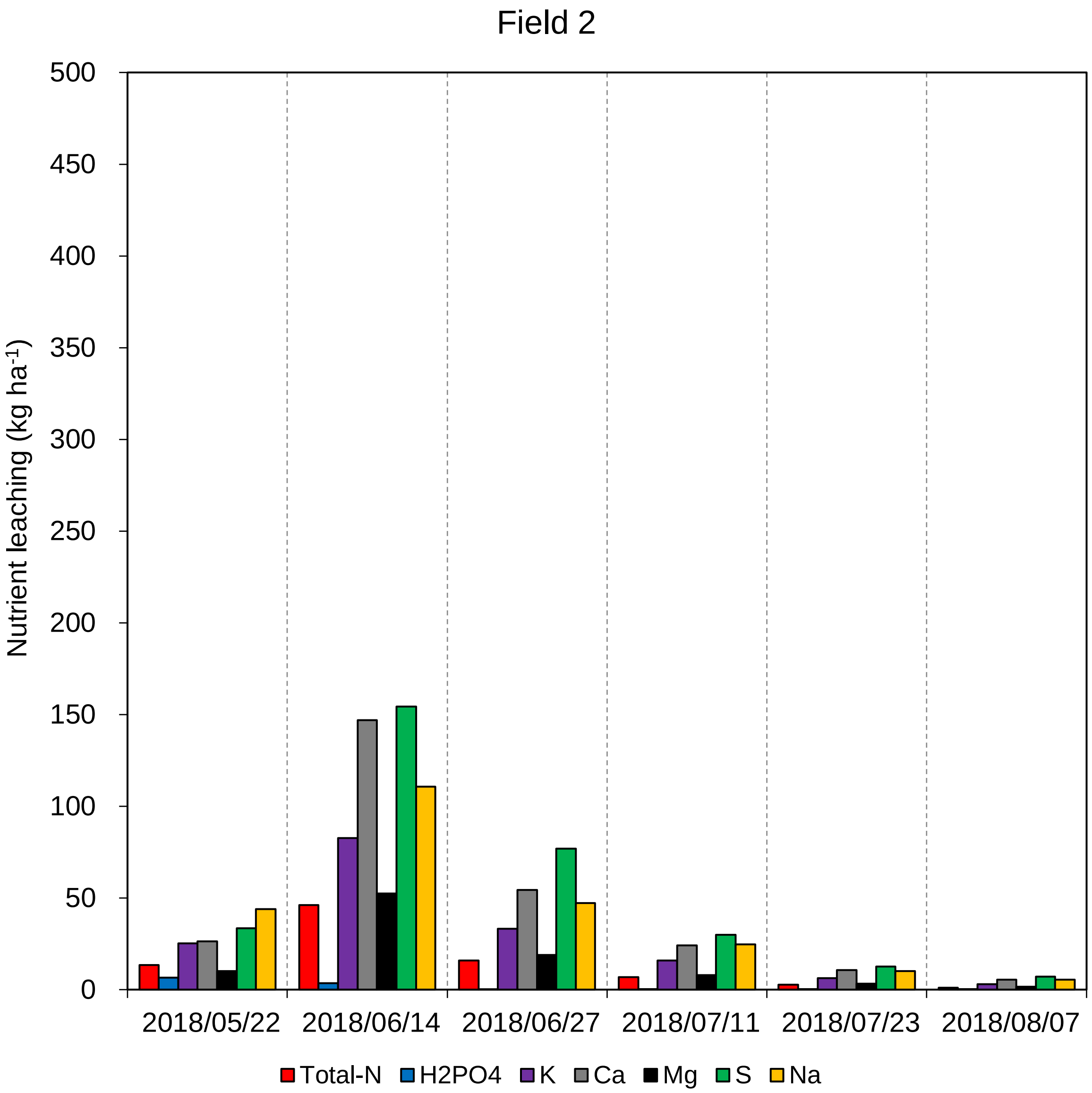

Figure 4.39. Nutrient leaching from Field 2 as measured from fortnightly drainage solution collected from the drainage lysimeter.

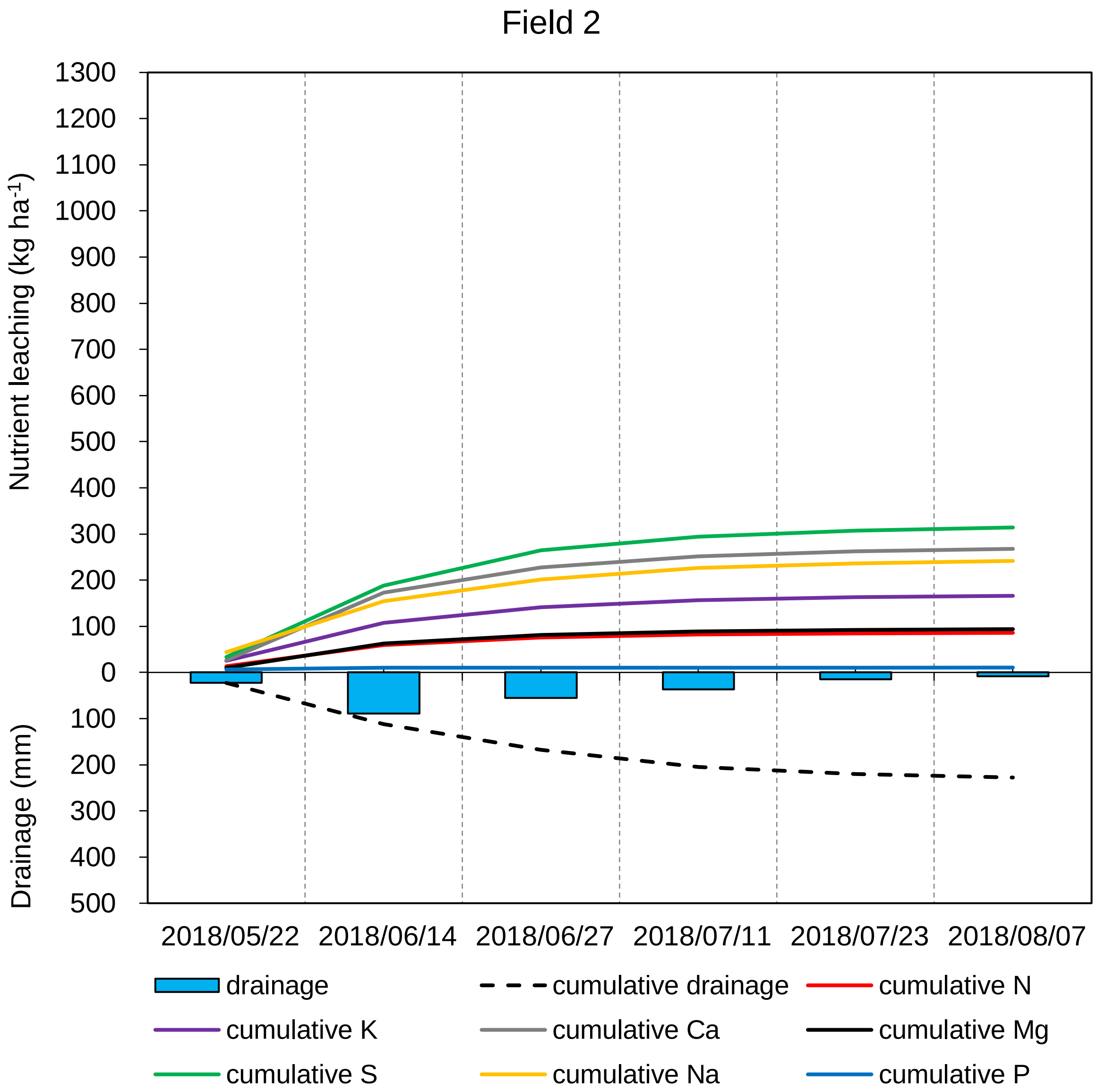

Figure 4.40. Cumulative macronutrient leaching compared to drainage amounts for Field 2.

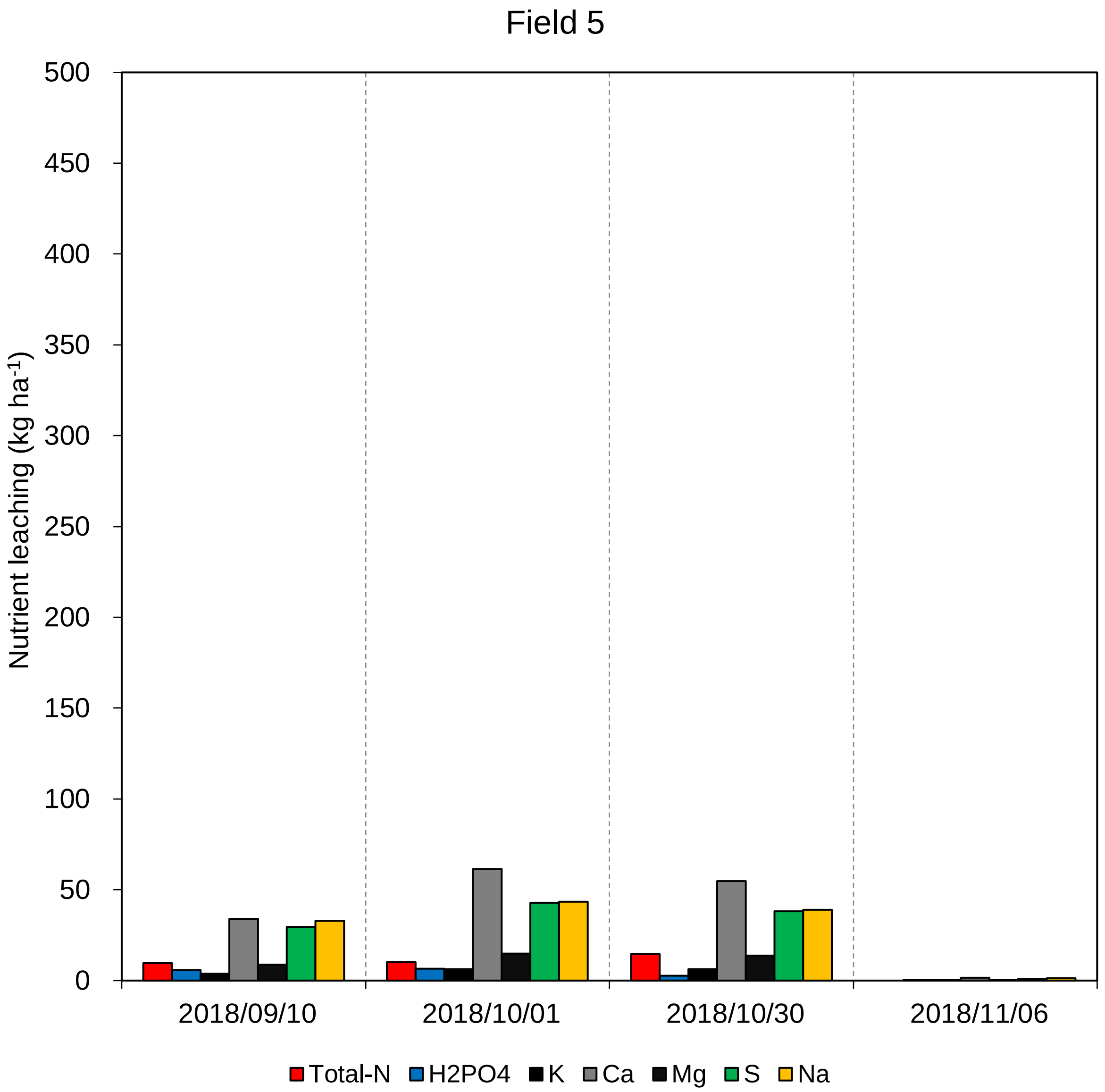

Figure 4.41. Nutrient leaching from Field 5 as measured from drainage solution collected fortnightly from the drainage lysimeter.

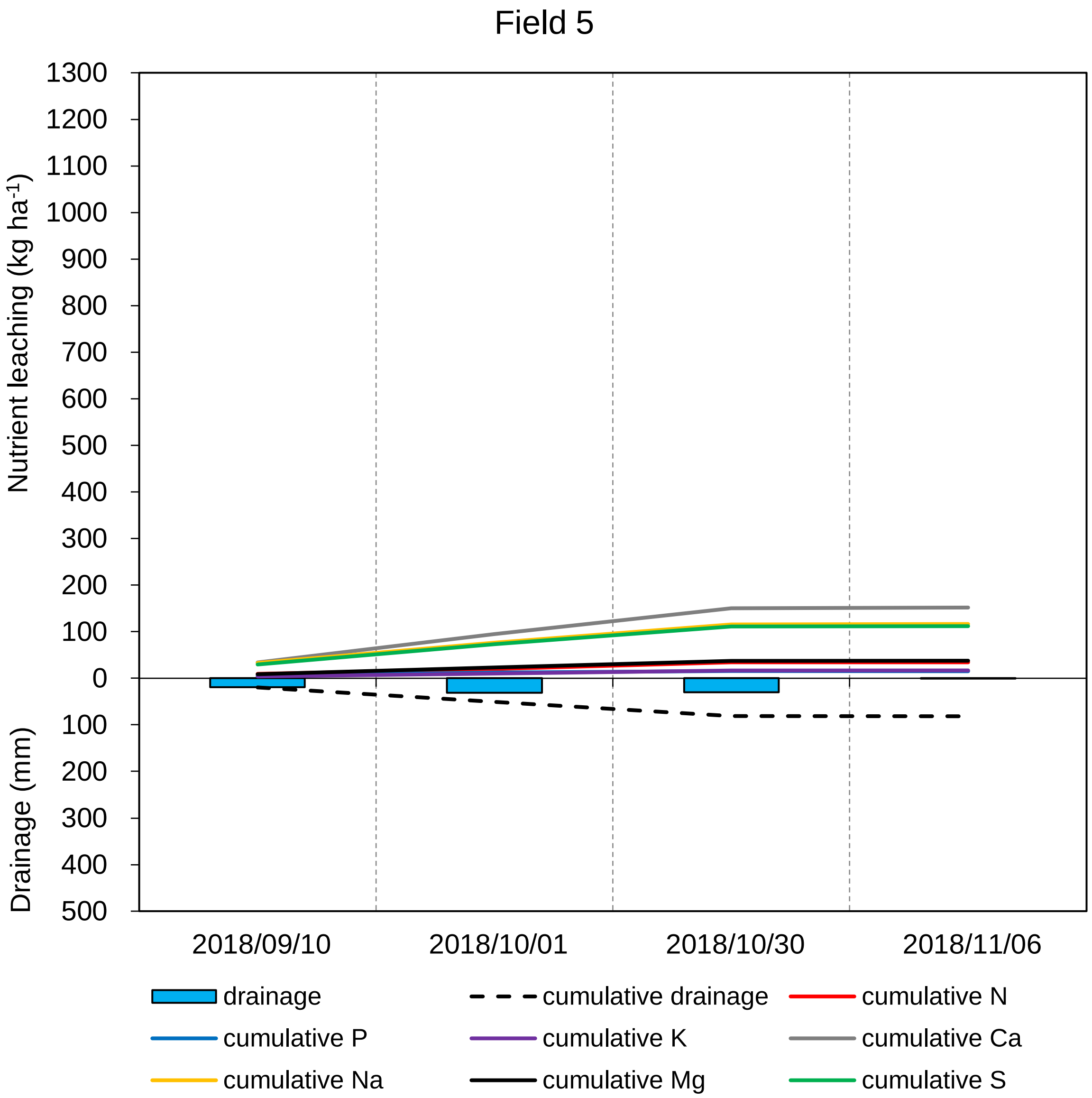

Figure 4.42. Cumulative macronutrient leaching compared to drainage amounts for Field 5.

The highest nutrient leaching was recorded for the two summer planted crops. For Field 8 (Figures 4.43 and 4.44) the rapid incline in nutrient leaching in Figure 4.43 was a result of 26.2 mm of rainfall received on the 7th of December, which occurred between the second and third sample dates (5 December to 7 January). Irrigation was not adjusted according to the rainfall received and between the sampling dates a total of 310.2 mm irrigation was applied, giving a total water input from rainfall and irrigation of 350.2 mm for this period. The cumulative nutrient leaching for Field 8 was substantially more than the other fields, amounting to 900 kg Ca ha^{-1}, 814 kg S ha^{-1} and 409 kg Na ha^{-1}. This can be attributed to the high amount of irrigation water applied (913 mm). The application of Ca, S and Na through irrigation water alone for Field 8 amounted to 48 kg Ca ha^{-1}, 40.3 kg S ha^{-1} and 919 kg Na ha^{-1} for the season. Field 9 produced 302 mm of drainage due to a high irrigation frequency, resulting in large nutrient losses below the root zone (Figures 4.45 and 4.46). The high leaching rates observed follows the trend of drainage collected (Figure 4.46). Total accumulated nutrients for the season were highest for Na > S > Ca, amounting to 1221 kg Na ha^{-1}, 927 kg S ha^{-1} and 542 kg Ca ha^{-1} and can be largely accredited to the irrigation water. The analysed water source contained 1.94 kg Na ha^{-1} mm^{-1}, 1.15 kg S ha^{-1} mm^{-1} and 0.44 kg Ca ha^{-1} mm^{-1}. Between sampling dates 30th of January and 19th of February the N, K, Ca, Mg, and S contents in the leachate decreased, however, irrigation application remained the same. This decrease can be attributed to the crop growth stage, which coincided with tuber initiation and bulking. The decrease in leaching from the third sample date to the fifth (19 February to 27 March) was due to the reduction in irrigation amount and frequency.

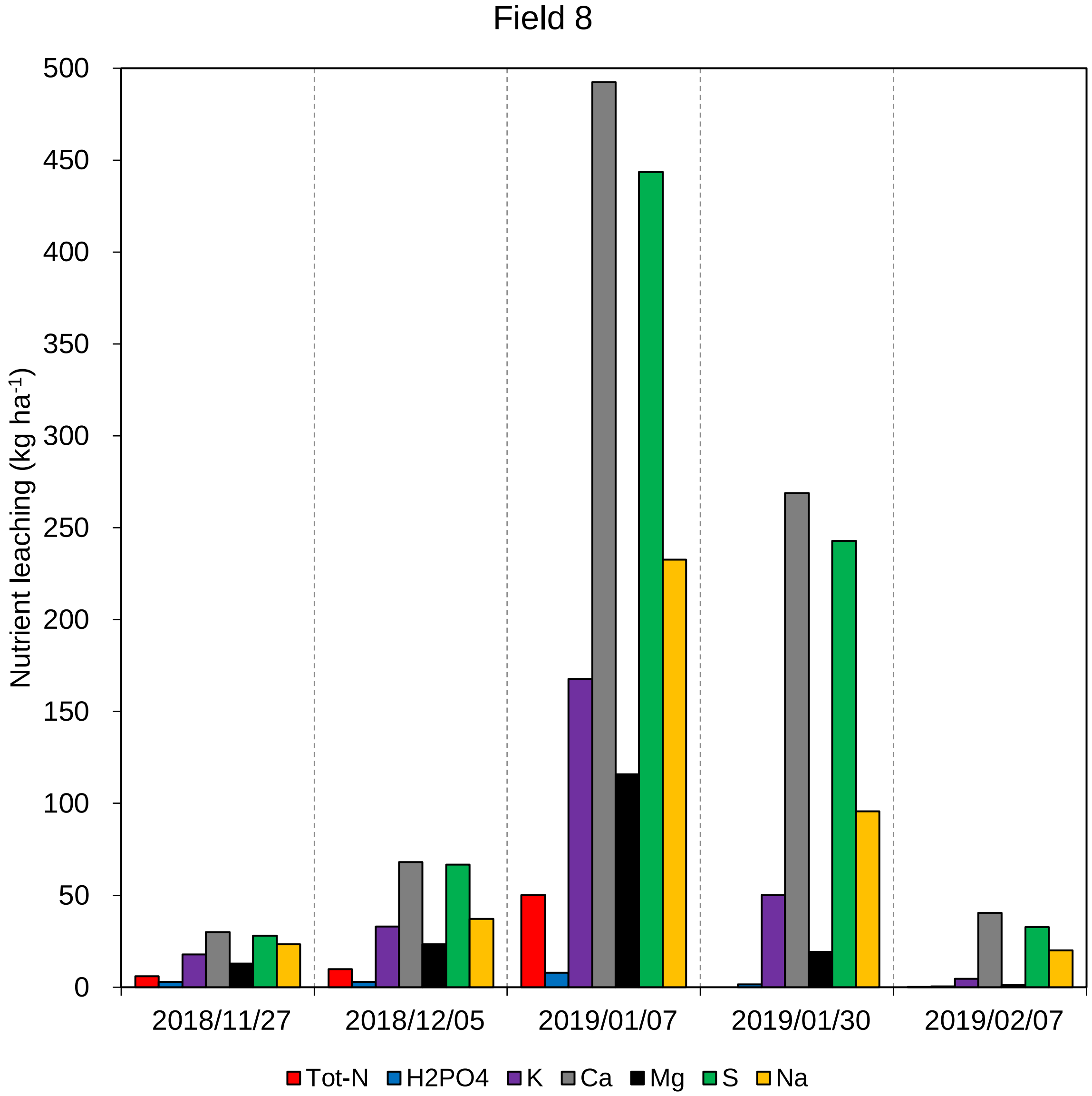

Figure 4.43. Nutrient leaching from Field 8 as measured from drainage solution collected fortnightly from the drainage lysimeter.

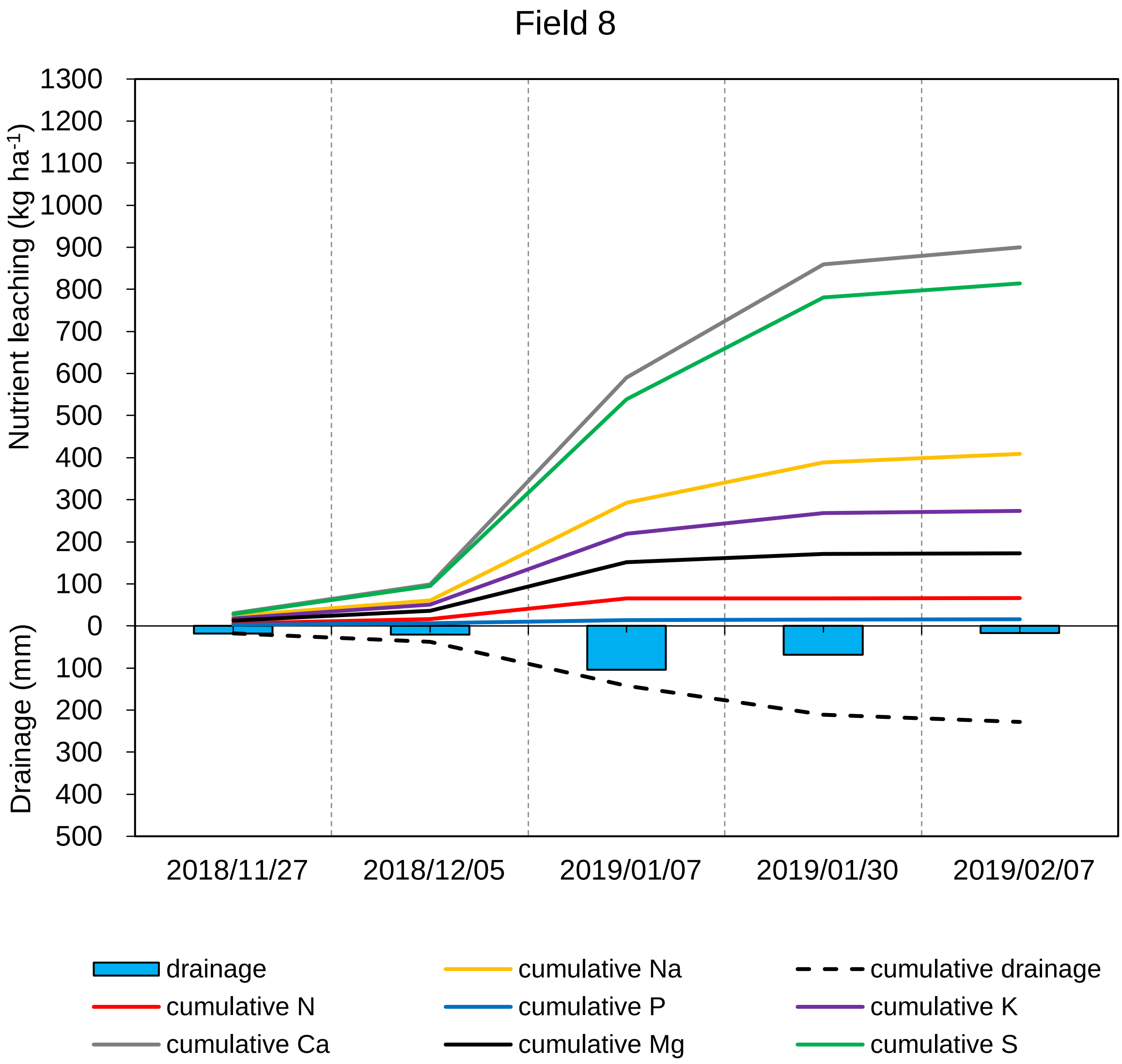

Figure 4.44. Cumulative macronutrient leaching compared to drainage amounts for Field 8.

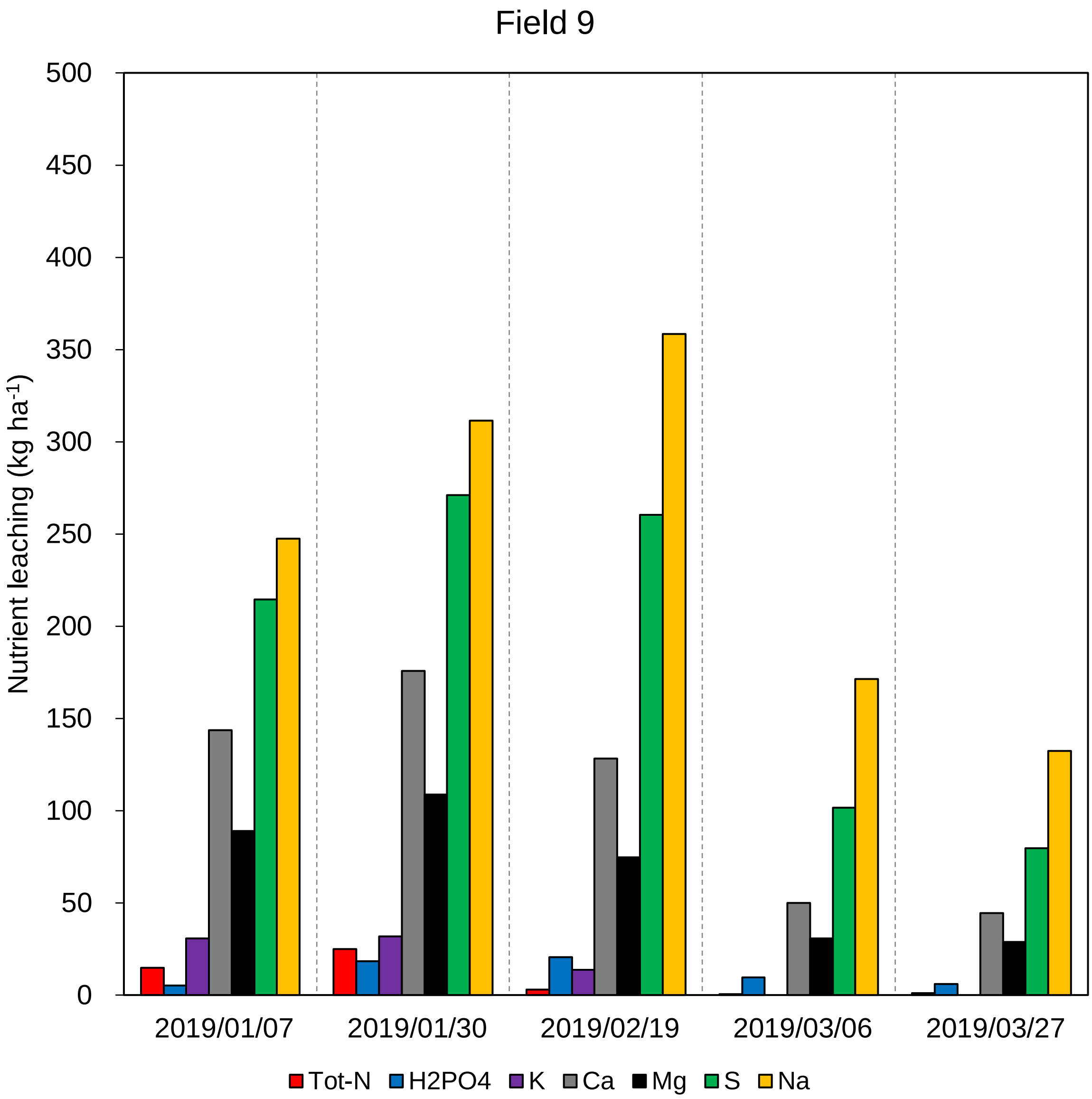

Figure 4.45. Nutrient leaching from Field 9 as measured from drainage solution collected fortnightly from the drainage lysimeter.

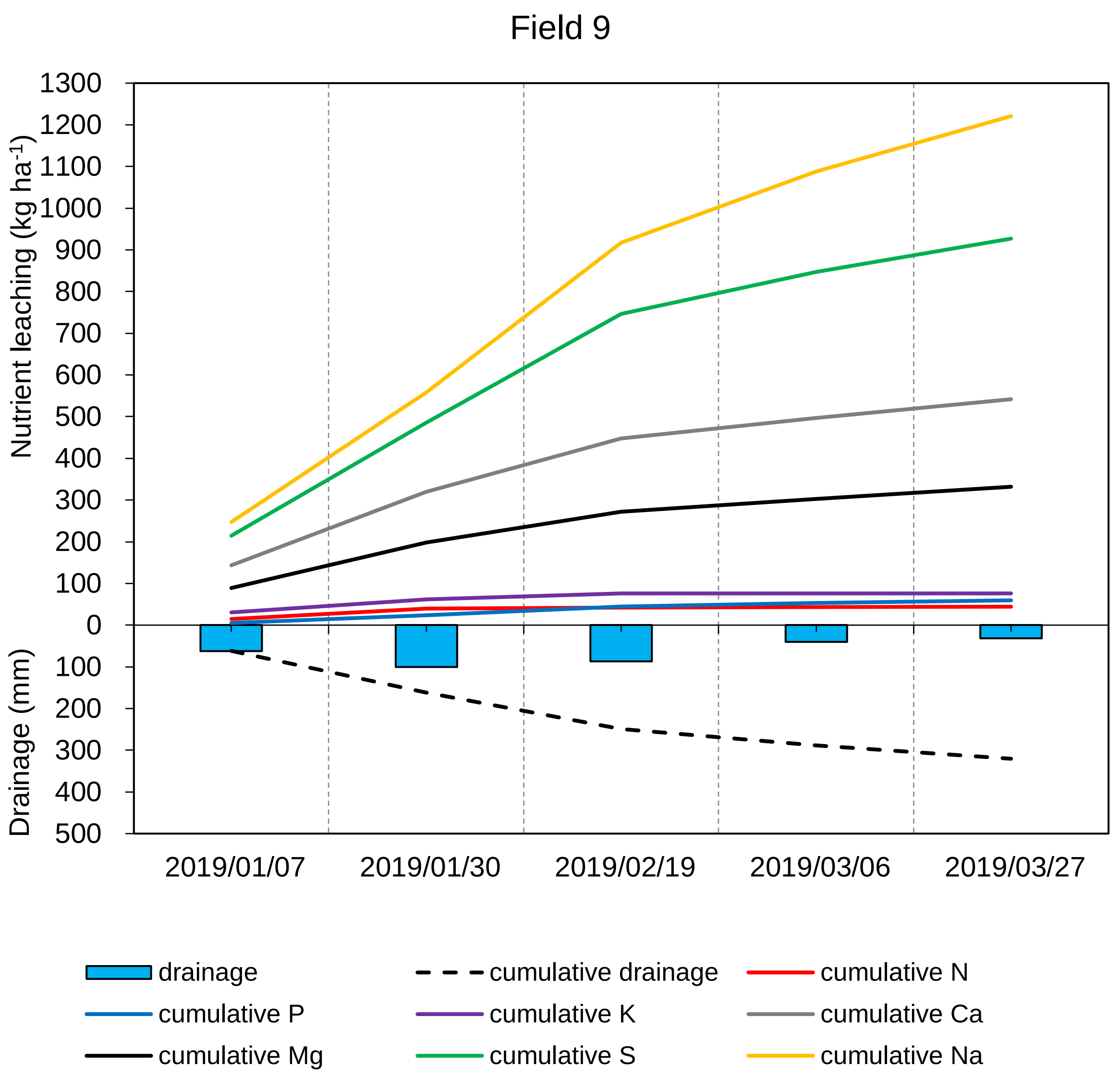

Figure 4.46. Cumulative macronutrient leaching compared to drainage amounts for Field 9.

The highest leached nutrient was Na, Ca, S with the lowest leached being P and N. The reason for high levels of Na, Ca, and S in the leached solutions was a result of various factors. The application of 2-3 t of gypsum ha^{-1} prior to planting on all fields, except Field 9, as well as the use of S containing products early on in the growth contributed to high levels of Ca and S in the soil profiles. All three nutrients (Na, Ca, and S) as well as Mg, but especially Na, resulted from high concentrations present in water sources.

It is generally assumed that nitrate and sulphate are the most easily leached from soils due to their negative charge. However, the results in Table 4.10 indicate that large quantities of the cations Mg, Ca and K leached from these sandy soils due to the lack of cation exchange sites associated with the soil type. In some instances (Fields 3 and 9) there were also large amounts of P leached, with Field 3 reaching 160 kg of leached P per ha^{-1} and Field 9 reaching 60 kg P ha^{-1}. Phosphorus is generally an immobile ion that is easily precipitated by other ions (Degryse et al. 2013; Vet et al. 2014). The high amounts of leached P in certain fields indicates the sensitivity of the Sandveld cropping system and the ease at which all nutrients are leached below the effective rooting depth of a potato plant, especially in occurrence with large water application from rainfall events.

Table 4.10. Extent of nutrients leached per season in intensively monitored fields.

	Nutrient leached kg ha^{-1}						
Field	N	P	K	Ca	Mg	S	Na
2	86	11	166	268	94	314	242
3	118	160	160	242	43	170	372
5	34	15	17	152	38	112	116
7	0	0	0	0	0	0	0
8	66	16	273	900	173	814	409
9	44	60	76	542	332	927	1221
Mean	70	52	138	421	136	467	472
Max	118	160	273	900	332	927	1221
Min	34	11	17	152	38	112	116

The results obtained in this study indicate the low capacity of the sandy profiles to bind cations such as Ca^{2+}, K^{+}, Mg^{2+} and Na^{+} as well as anions. This is in agreement with previous studies (Chantigny et al. 2004; Yang et al. 2007). Tahir and Marshchner (2017) studied the effects of clay addition to nutrient leaching in sandy soils. The study concluded that the addition of clay considerably increased fertiliser nutrient retention. When compared to pure sandy soils, clay amended soils resulted in 83% more N and double the P retention.

Although substantial P leaching was observed for some fields in this study, the amounts were generally far less than that reported by Chen et al. (2006), who indicated that 97% of P applied through water-soluble fertilisers was leached from sandy soils and < 1% was leached when using dolomite phosphate rock. The dolomite phosphate rock, which acted as a slower releasing fertiliser, produced better results when used in acidic sandy soils. However, the study also concluded that 68 to 99.9% of the leached P was in the readily available form, which is problematic for aquatic systems as it is easily available to algae, increasing the potential risk of eutrophication. In the present study an average of 52 kg P ha^{-1} leached below

1 m depth. Highest P leaching was recorded for Field 3 (160 kg P ha^{-1}) and the lowest in Field 7 (0 kg P ha^{-1}).

A study in Zimbabwe showed that 54% of applied N was leached from the 0 to 0.5 m soil profile, following heavy rainfall on sandy soils (Hagmann 1994). Results obtained for the Sandveld showed the same trend in leachate increase after large rainfall events. It was evident that in the Sandveld region, farmers prefer the use water-soluble fertiliser products for practicality reasons and hence the majority of nutrients are applied through fertigation via the centre-pivot, with the exception of gypsum, which may increase the potential for leaching to occur.

The total loss of nutrients via leaching is highly dependent on the amount of drainage associated with excessive water from rainfall or over-irrigation, which is in agreement with Shepherd and Bennet (1998) and Jiang et al. (2011). The rate of nutrient losses in sandy soils, however, varies considerably within the literature. Ruskowska et al. (1984) indicated that with no influence from fertiliser rate, only 5 kg K ha^{-1} leached from sandy soils. This was considerably lower than results obtained in the present study. The high nutrient leaching can potentially be attributed to the use of water-soluble fertilisers in the Sandveld region. Catanzaro et al. (1998) showed that the use of liquid fertilisers increased leachate of N collected in a chrysanthemum pot trial by 14 to 20%. Yang et al. (2007) indicated that the use of chemical fertilisers alone in sandy soils increased P concentration in leachate 10 to 20 times, compared to a control. The combination of high-water inputs into the field (rainfall and irrigation) as well as the use of water-soluble fertilisers applied even during rainfall events in a practice referred to as '*high tech fertigation*'. This practice results in the application of high concentrations of nutrients to the soil through the centre-pivot to maintain nutrient levels within the profile.

4.2.7 Leachate EC levels

The drainage lysimeter sensor measured EC of the collected solution throughout the growing season (Figure 4.47). For all fields, with the exception of Field 7, the leachate EC reached values above 150 mS m^{-1}. For Fields 2 and 5 the leachate collected started below 150 mS m^{-1} but once drainage occurred, within a day or two, the EC moved just above 170 mS m^{-1}. The leachate for Fields 2 and 5 reached a maximum EC of 228 and 202 mS m^{-1}, respectively. Field 2 remained above the 170 mS m^{-1} for 39 days when it then declined to 96 mS m^{-1} and remained at a relatively stable EC until the end of the season, with dips at 91 and 106 days after the lysimeter was installed. These dips in EC were attributed to drainage solution removal. For Field 5 the EC remained stable from day 12 to day 70 when it then declined sharply to 8.3 mS m^{-1} and remained low thereafter. At day 70, 30 mm of soil solution was removed and from then on 42.1 mm of irrigation was applied, however, very little drainage (0.6 mm) occurred from day 70 to the end of growth. Field 3 started with a very high EC of 388.5 mS m^{-1}, but this reduced throughout the season, reaching below the 150 mS m^{-1} 39 days after lysimeter installation. This was after substantial water application had occurred through rainfall and irrigation (refer to Figure 4.4) along with a period of low ET. Therefore, drainage accumulated and possibly caused a dilution of EC within the drainage lysimeter. The leachate collected during summer grown fields (Fields 8 and 9) had substantially higher EC levels throughout the season in comparison to winter grown fields. Field 8 remained below 100 mS m^{-1} until 36 days after the drainage lysimeter was installed. The EC then increased (180.1 mS m^{-1}) and remained above 150 mS m^{-1} for the rest of the season, then declined to below 170 mS m^{-1} 102 days after lysimeter installation. Field 9, which was located close to the ocean, maintained a leachate solution EC above 225 mS m^{-1} throughout the season.

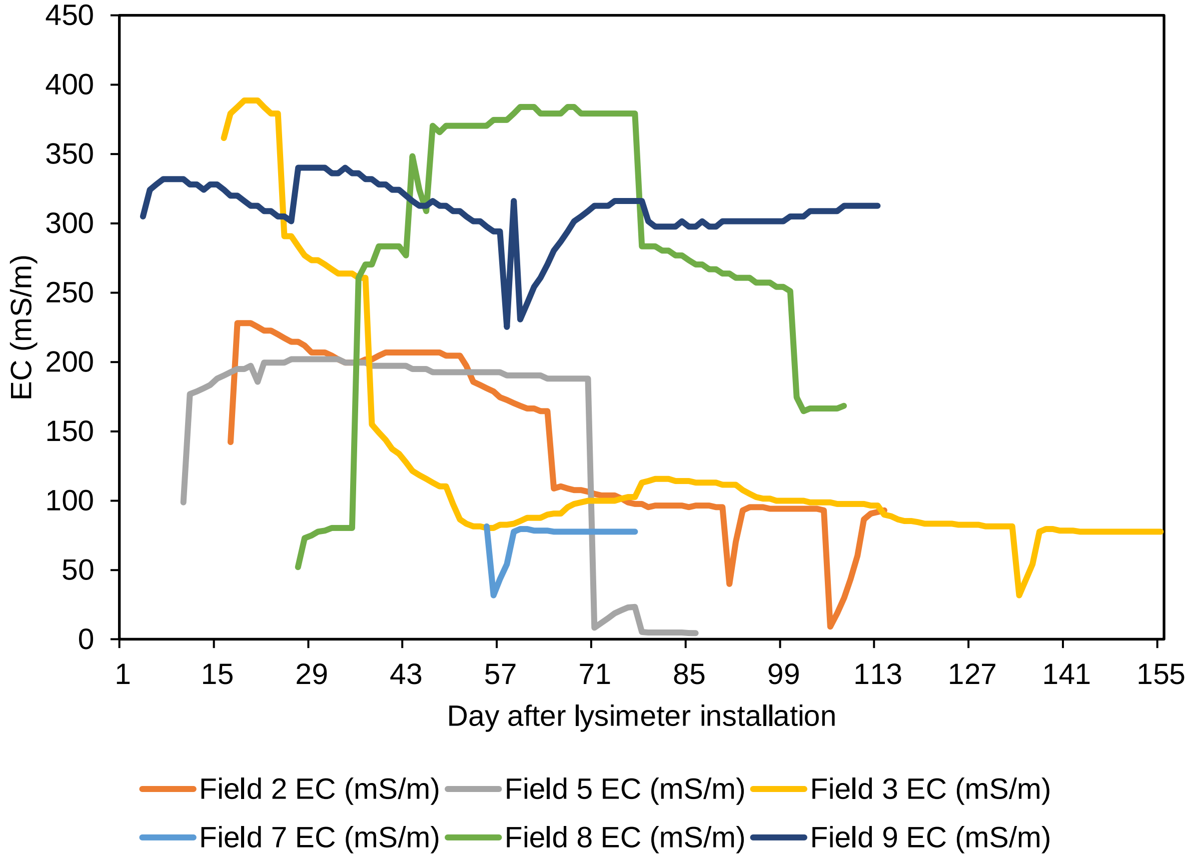

Figure 4.47. Variation in drainage solution EC throughout crop growth for intensively monitored fields.

A study conducted by Letey et al. (2011) indicated that negative effects caused by irrigating with saline water were significantly moderated by rainfall due to a dilution effect. Both summer-grown fields in the Sandveld maintained a higher EC value throughout the season, which can be attributed to the higher irrigation frequency and amounts, quality of irrigation water and lack of rainfall (refer to Figures 4.9 and 4.10). It was evident that for winter planted crops the leachate EC levels were lower and was attributed to substantial and periodic rainfall events, which leached out and diluted excess salts. However, the effect of fertiliser application, which is carried out on a weekly basis in the Sandveld region, cannot be neglected on the role it may play on the EC levels of the collected leachate. Large pre-planting application of fertilisers may have resulted in initially high EC values observed at the start of the seasons, which coincides with when majority of the N leaching occurred and can be attributed to small crops and shallow root systems during this period. The reduction in leachate EC levels observed later on in the crop seasons was due to a decline in fertiliser applications.

4.3 Plant nutrient uptake

4.3.1 Leaf tissue nutrient content

The amount of leaching partly depends on the capacity of a potato plant to uptake nutrients at various stages during the growth cycle. This can be illustrated through leaf samples analysed throughout the season, as well as nutrient content within the tuber during harvest. Leaf samples showed similar trends, with N and K being present at high concentrations throughout growth, followed by Ca. Nitrogen dropped slightly towards the end of the growth cycle, whereas Ca is found at higher concentrations at the end of growth than during the start (Table 4.11).

Six out of the nine fields under observation showed a decrease in N content for samples conducted 67 days after emergence (DAE) and onwards, with the exception of Fields 3 and 9. The latest leaf samples taken were at 92 DAE. Deficient N values are regarded as below 4.5% (Haifa Group Ltd (2019) and Yara UK Fertiliser (Pty) (2019)). Fernandes and Soratto (2016) reported an N leaf content of 5.1% (51 g kg^{-1}) between 29 and 33 DAE. This coincides with the average value of 5.7% obtained in the present study for fields sampled at a similar time (26 – 35 DAE). Kolbe and Stephan-Beckmann (1997) reported the maximum value of leaf N concentration at 30 DAE, which also coincides with values obtained in the present study, where leaf samples were taken during a similar time (26 – 35 DAE). The N values attained were between 5.13 and 6.16%. However, samples taken within 14 DAE showed excessive leaf N concentrations (>7.0%). The high N concentrations indicate high absorption and translocation of N during the early stages of growth, which coincides with the vegetative stage. Towards the end of the tuber-bulking stage, a decline in leaf tissue N content is observed. At the time of maximum N plant uptake (55 – 65 DAP), as reported by Zotarelli et al. (2015), leaf tissue values for fields analysed (Fields 2, 3, 7, 8 and 9) close to this time ranged from 4.38 to 6.16% (norm: 4.5 – 6.5%), indicating that N levels in these crops were adequate for growth. Field 9, however, had slightly low leaf N levels at 4.38%, but was not deficient. The N values obtained in the current study are higher than the values reported by Ries and Monnerat (2000), who indicated an average leaflet N value of 3.99% 48 DAE. Maximum leaf tissue organic and inorganic component contents are said to be reached 45 to 50 DAE and highest growth rates between 30 and 45 DAE (Kolbe and Stephan-Beckmann 1997).

Sufficient P content in the leaf early in the season is regarded as 0.44% (Walworth and Muniz 1993). Phosphorus leaf tissue values in the literature are reported to be very low in potato crops and range from 0.21 to 0.55%. (Walworth and Muniz 1993; Rocha et al. 1997; Ries and Monnerat 2000; Fernandes and Soratto 2016). The average leaf P content for the region (0.53%), conducted during this study, was within the range reported in the literature (Walworth and Muniz 1993; Rocha et al. 1997; Ries and Monnerat 2000; Fernandes and Soratto 2016). Fields sampled 10 to 41 DAE showed excess P concentrations ranging from 0.60 to 0.83%. All K concentrations were below the recommended norms (4 – 10%) throughout the growth cycle. Sharma and Arora (1987) indicated a decrease in potato leaf K content with an increase in DAE. An average value of 3.12% for K was observed from all leaf samples conducted in the present study. The Mg concentrations measured ranged from 0.33 to 1.65%, with 66% of the samples producing average results >0.5%. Fernandes and Soratto (2016) reported an average of 0.7% leaf Mg content with no effect of site, cultivar or P rate on the content of N, K, Ca, Mg, S, B, Cu, Fe and Mn. In comparison, Bergmann (1992) stated an adequate range in leaf tissue Mg content between 0.25 and 0.8% for potato crops and sugar beet. Values below or above this range will result in deficient or excess Mg contents, respectively. According to the values stated by Bergmann (1992), 50% of the leaf samples had an average Mg leaf content of >0.8% and therefore, average leaf Mg concentrations (0.76%) in this study were in agreement with those reported in the literature. The low levels of K observed in the present study can possibly be attributed to the antagonism between K^+ and Mg^{2+} ions. Ries and Monnerat (2000) reported a similar effect. To indicate this antagonistic behaviour between cations, Addiscott (1974) reported a decrease in both Mg and Ca with an increase in K_2SO_4 fertiliser application. The high Ca levels observed in the leaf tissue could also be a contributing factor to the low K contents observed. An average of 1.49% Ca, with a maximum value of 3.03% was recorded. The adequate levels of Ca in the leaf tissue can be accredited to the high levels of Ca seen in the soil analysis due to the practice of gypsum application prior to planting. All S levels were within normal ranges, with the exception of Field 8.

The S values for Field 8 dropped below 0.25% towards the end of the growth cycle (67 – 90 DAE). The adequate S levels can be attributed to both pre-planting gypsum applications as well as the application of K_2SO_4 fertiliser, resulting in an abundance of S movement through the plant root zone.

Table 4.11. Leaf analysis conducted for Fields 2 to 9 approximately every 30 to 40 days. Leaf sampling commenced once good vegetative growth was established. Field 1 data is missing due to the need for sampling made clear after its early termination due to late blight (*Phytophthora infestans*).

		Leaf nutrient content (%)						
Field	DAP	N	P	K	Ca	Mg	S	Na
Field 2	27	7.04	0.64	3.82	1.18	0.63	0.34	0.02
	55	5.78	0.57	2.84	1.70	0.90	0.38	0.06
	105	3.73	0.42	4.34	1.90	0.90	0.38	0.17
Field 3	43	5.91	0.60	3.63	1.22	0.39	0.40	0.03
	68	6.16	0.69	4.30	0.97	0.42	0.36	0.07
	96	5.08	0.46	3.79	2.14	0.66	0.31	0.07
Field 4	46	6.21	0.66	3.22	0.97	0.38	0.40	0.03
	82	5.00	0.53	3.07	1.15	0.44	0.31	0.04
	102	4.16	0.46	2.23	3.03	0.88	0.30	0.11
Field 5	96	5.01	0.52	3.70	1.90	0.98	0.35	0.08
	125	3.22	0.38	2.14	2.52	0.91	0.28	0.37
Field 6	28	7.57	0.78	2.83	0.70	0.40	0.48	0.02
	84	5.81	0.53	3.01	1.08	0.73	0.35	0.11
	113	3.12	0.35	2.21	2.40	1.12	0.31	0.84
Field 7	21	6.32	0.83	3.76	0.77	0.33	0.36	0.02
	62	6.08	0.60	3.86	1.15	0.50	0.42	0.03
	91	3.44	0.26	2.36	2.91	0.95	0.29	0.28
Field 8	47	5.13	0.74	3.29	0.68	0.35	0.35	0.08
	55	5.54	0.67	3.48	1.01	0.45	0.37	0.06
	88	3.67	0.39	2.56	1.90	1.09	0.24	0.45
	111	2.77	0.38	2.33	1.96	1.40	0.21	0.84
Field 9	38	6.12	0.61	3.06	0.69	0.87	0.38	0.18
	61	4.38	0.38	2.38	1.05	1.65	0.34	0.47
	81	5.17	0.36	2.68	0.88	0.98	0.40	0.47
Mean		5.10	0.53	3.12	1.49	0.76	0.34	0.20
Max		7.57	0.83	4.34	3.03	1.65	0.48	0.84
Min		2.77	0.26	2.14	0.68	0.33	0.21	0.02

4.3.2 Tuber nutrient content

Average tuber nutrient contents (Table 4.12) in the Sandveld were highest for N (1.41%) and K (1.89%), which follows a similar trend to those reported by Alvarez et al. (2006) and Fernandes et al. (2017). Average tuber N and K contents in the present study (1.41 and 1.89%, respectively) were in the same range as that reported by Alvarez et al. (2006) for a control crop under soils high in nutrient availability. Selladurai and Purakayastha (2016) reported tuber nutrient contents for N, P and K of 1.78, 0.17 and 1.00%, respectively. The reported tuber N content was higher than obtained in the present study. However, P and K levels were higher in the Sandveld region. For Fields 2 and 5 the tuber N content was 1.85% and 1.81%, respectively, which was similar to values reported by Fernandes et al. (2017) of tuber N content at 1.83%. All other fields, however, obtained lower N tuber contents. On the other hand, the average K, Ca and Mg tuber contents obtained were substantially lower (1.89, 0.02 and 0.09%, respectively) than that reported by Fernandes et al. (2017) at 3.05, 0.37 and 0.22%, respectively. Phosphorus tuber content ranged from 0.24 to 0.34% for all fields, with the exception of Fields 1 and 4. The tuber P nutrient contents observed were higher than the average reported by Soratto et al. (2015) (0.26%) and Soratto and Fernandes (2016) (0.19%) for the cultivar Mondial. However, in their study soils containing high P levels within the root zone (~111 $mmol_c\ dm^{-1}$) were observed to have higher tuber P contents (0.33%), which was closer to values obtained in the present study. This indicates the influence of soil P levels on tuber P content as various soils in the Sandveld were seen to have high levels of P (Appendix II). It is evident that the general trend in nutrient content for potatoes, as viewed in the literature, is highest with regards to N and K. This is in agreement with results observed in the Sandveld.

Table 4.12. Tuber nutrient contents from the yield analysis conducted for each monitored field. The pith analysis was selected to represent the entire tuber nutrient content due to the large proportion of the pith in comparison to the skin and medulla.

	Tuber nutrient content (%)						
Field	N	P	K	Ca	Mg	S	Na
Field 1	1.53	0.24	1.66	0.01	0.09	0.12	0.03
Field 2	1.85	0.31	1.76	0.02	0.10	0.14	0.03
Field 3	1.54	0.31	1.97	0.01	0.11	0.14	0.05
Field 4	1.01	0.26	1.66	0.01	0.09	0.11	0.04
Field 5	1.81	0.34	1.84	0.02	0.10	0.15	0.04
Field 6	1.21	0.30	1.72	0.01	0.09	0.12	0.04
Field 7	1.22	0.31	2.03	0.02	0.10	0.13	0.05
Field 8	1.10	0.31	2.20	0.02	0.08	0.10	0.04
Field 9	1.38	0.33	2.17	0.02	0.09	0.14	0.07
Mean	1.41	0.30	1.89	0.02	0.09	0.13	0.04
Max	1.85	0.34	2.20	0.02	0.11	0.15	0.07
Min	1.01	0.24	1.66	0.01	0.08	0.10	0.03

A clear trend in tuber nutrient content distribution between the skin, medulla and pith was observed (Tables 4.12, 4.13 and 4.14). The proportion of total tuber nutrients that were present in the tuber skin alone were observed to be greater than the proportion of total nutrients that was present in the flesh of the tubers (pith and medulla) (Table 4.13). The high proportion of nutrients in the skin may be a result of direct uptake from the soil across the periderm, as suggested by Subramanian et al. (2011). This follows a similar trend as reported by Boydston et al. (2018) and is in agreement with Trehan and Sharma (1996) and Sulaiman (2005). The average nutrient contents observed in the Sandveld within the skin for N (2.30%), K (3.52%) and P (0.41%) where higher compared to the tuber flesh (pith), followed by S, Mg, Ca and Na. The reason for the concentration difference in the tubers is reported to be a factor of the mobility of ions within the plant. Calcium is passively transported through the plant in the transpiration stream. Due to the low transpiration rate of tubers, less Ca was present in tubers analysed in the Sandveld (0.02%) compared to aboveground plant parts, as illustrated by leaf analysis results. Nitrogen and K, on the other hand, are easily re-translocated from aboveground plant parts to the tuber and hence, are present at much higher concentrations within the tubers. Tubers are generally considered high in K concentrations (White et al. 2009). The contribution of the nutrients in the tuber skin to overall tuber nutrient content would, however, be small in comparison to the pith due to the minor mass that the skin contributed to total tuber mass. This is the reason for excluding the skin nutrient contents when calculating tuber nutrient removal. Nutrient uptake and distribution are reported to be largely controlled by cultivar factors (LeRiche et al. 2006), if soil nutrient content is not limiting. However, there was no substantial differences observed between nutrient contents of the skin, medulla and pith for the cultivars Sifra and FL2108 used in the present study.

Table 4.13. Nutrient content for the skin of potato tubers harvested from monitored fields.

	Skin nutrient content (%)						
Field	N	P	K	Ca	Mg	S	Na
Field 1	2.59	0.31	3.51	0.09	0.16	0.16	0.02
Field 2	2.99	0.38	2.99	0.09	0.15	0.18	0.02
Field 3	2.78	0.50	3.64	0.09	0.18	0.16	0.02
Field 4	1.88	0.44	4.22	0.08	0.15	0.15	0.03
Field 5	2.81	0.53	3.14	0.12	0.17	0.18	0.04
Field 6	1.99	0.46	2.99	0.08	0.14	0.18	0.03
Field 7	2.36	0.41	4.36	0.08	0.15	0.17	0.04
Field 8	1.63	0.35	3.76	0.08	0.12	0.11	0.06
Field 9	1.66	0.29	3.09	0.07	0.15	0.18	0.09
Mean	2.30	0.41	3.52	0.08	0.15	0.16	0.04
Max	2.99	0.53	4.36	0.12	0.18	0.18	0.09
Min	1.63	0.29	2.99	0.07	0.12	0.11	0.02

Table 4.14. Nutrient content of the medulla section of potato tubers harvested from monitored fields.

	Medulla nutrient content (%)						
Field	N	P	K	Ca	Mg	S	Na
Field 1	1.37	0.31	2.42	0.03	0.09	0.12	0.02
Field 2	1.40	0.35	2.50	0.03	0.09	0.12	0.03
Field 3	1.33	0.36	2.72	0.03	0.10	0.12	0.03
Field 4	0.83	0.26	1.87	0.02	0.06	0.07	0.03
Field 5	1.49	0.37	2.29	0.04	0.09	0.12	0.04
Field 6	1.14	0.35	2.29	0.03	0.09	0.11	0.04
Field 7	1.22	0.31	2.27	0.02	0.09	0.11	0.05
Field 8	0.93	0.30	2.08	0.03	0.06	0.08	0.06
Field 9	0.97	0.30	2.32	0.03	0.07	0.12	0.10
Mean	1.18	0.32	2.31	0.03	0.08	0.11	0.04
Max	1.49	0.37	2.72	0.04	0.10	0.12	0.10
Min	0.83	0.26	1.87	0.02	0.06	0.07	0.02

The maximum nutrient removal for all fields by tubers was 541 kg K ha^{-1}, 271 kg N ha^{-1},76 kg P ha^{-1}, 4.9 kg Ca ha^{-1}, 18 kg Mg ha^{-1}, 24 kg S ha^{-1} and 11 kg Na ha^{-1}, which was obtained by Field 8. The high values can be attributed to the very high yield obtained. However, tuber nutrient removal (Table 4.15) did not indicate a clear correlation with yield for all fields monitored, which is in agreement with values reported in the literature. Average N removal by tubers in the Sandveld was 167 kg ha^{-1}. Trehan et al. (2008) reported the removal of 120 to 140 kg N ha^{-1} for potatoes grown in India. Sandveld tuber N removal was also more than the tuber nutrient removal as reported by Haase et al. (2007) (127 kg N ha^{-1}) under organic farming conditions in Germany, producing a crop of 31 t ha^{-1}. Rens et al. (2016) reported tuber N removal of 117 and 142 kg ha^{-1} for cultivars Atlantic and FL1867, respectively, for crops receiving a total fertiliser application of 225 kg N ha^{-1}. Average tuber N removal in the Sandveld was 52% greater than that reported by Mohamed et al. (2017). The present study obtained higher N, P, K and S tuber nutrient removal than that reported in Brazil by Fernandes et al. (2017). However, the Ca and Mg tuber nutrient removal observed in the Sandveld was substantially lower than the values reported by Fernandes et al. (2017) for soils with medium P availability (36 mg dm^{-3}). Selladurai and Purakayastha (2016) reported N, P and K tuber content of 104, 10 and 58 kg ha^{-1} respectively, for chemical applied fertilisers. However, the fertiliser rates used in their study were much lower than those used in Sandveld farming practices. Jarrell and Beverly (1981) showed that an increase in DM production of plants and the higher DM yielding varieties resulted in a dilution effect of nutrients, however, this effect was not observed in the present study.

Table 4.15. Nutrient removal as influenced by the DM yield of tubers harvested from monitored fields.

		Tuber nutrient removal (kg ha^{-1})						
Field	Yield t DM ha^{-1}	N	P	K	Ca	Mg	S	Na
Field 1	7.5	115	18	125	0.8	6.4	9.0	2.0
Field 2	11.2	207	35	196	1.7	11	16	3.4
Field 3	9.0	139	28	178	0.9	10	13	4.3
Field 4	12.5	126	33	207	1.2	11	14	5.0
Field 5	10.8	196	36	199	2.2	11	16	4.4
Field 6	11.1	134	33	191	1.1	10	13	4.2
Field 7	11.7	143	36	237	2.0	11	15	5.4
Field 8	24.7	271	76	541	4.9	18	24	11
Field 9	12.3	170	40	267	2.8	11	18	9.1
Mean	12.3	167	37	238	2.0	11	15	5.4
Max	24.7	271	76	541	4.9	18	24	11
Min	7.5	115	18	125	0.8	6.4	9.0	2.0

Dry matter yield was calculated from an average SG value obtained for variety FL2108 of 1.083, which was converted to a DM content of 21.7%. For the variety Sifra the DM content was measured directly, giving an average of 20.9% for Fields 8 and 9.

The high tuber nutrient content and tuber nutrient removal of N and K is attributed to the high demand of both these nutrients by potato crops and reflects the high fertiliser application rates practiced in the region (Table 4.16). The low tuber removal of Ca is a result of the low mobility and distribution of Ca in the plants. It is evident from the literature and results that there is an effect of soil available P on the tuber P content. It is clear that tuber nutrient content is also a factor of the uptake and utilisation of various nutrients by potato crops.

Table 4.16. Total input of each nutrient element per field for the entire cropping cycle through fertiliser applications. Fertiliser regimes were generally similar within the region and applied on a weekly basis.

	Fertilisation (kg ha^{-1})					
Field	N	P	K	Ca	Mg	S
Field 1	240	118	217	457	6	296
Field 2	302	125	459	841	46	679
Field 3	294	189	454	924	41	677
Field 4	294	189	454	888	41	635
Field 5	302	125	459	841	46	679
Field 6	277	156	522	671	24	468
Field 7	288	167	495	603	59	433
Field 8	294	189	454	924	41	677
Field 9	302	118	443	217	8	106
Average	288	153	440	708	34	517
Maximum	302	189	522	924	59	679
Minimum	240	118	217	217	6	106

4.3.3 Nutrient use efficiency

Table 4.17 indicates the mean AUE values obtained from the study. The least applied nutrients through fertilisation, such as P and Mg, resulted in high AUE (378 and 2718 kg of yield obtained per kg of nutrient applied for P and Mg, respectively). It is evident that there was an increase in AUE with decreased fertiliser rates or an increase in yield. The effect of a decrease in AUE with increased fertiliser application is clearly observed for Field 9. The least amount of Ca in the region (217 kg ha^{-1}) was applied to this field owing to no gypsum application prior to planting. Due to this low Ca application, Ca AUE was the highest at 272 kg kg^{-1}. The results are in agreement with those of Hu et al. (2014), who concluded that AUE decreases with increasing fertiliser rates, unless tuber yield is significantly increased. This was also concluded by Gholipouri and Kandi (2012), who reported that 100 kg of N was more effective than 200 kg N, and is also aligned with results reported by Abbasi et al. (2011). Agronomic use-efficiency, however, is viewed as not an appropriate measure of NUE when comparing various management practices such as differing water regimes. It does, however, provide an accurate assessment of NUE for systems that are stable concerning soil organic N content and in crops that have negligible root nutrient contents (Dobermann 2005), such as is seen in the Sandveld region.

Table 4.17. Mean values of the nutrient efficiency parameters obtained in the Sandveld region, taken from all nine (extensively and intensively) monitored fields. AUE = Agronomic use efficiency.

Nutrient use efficiency parameters							
	N	P	K	Ca	Mg	S	Na
Haulm (kg ha^{-1})	37.3	5.8	25.6	26.1	10.8	4.2	6.3
Nutrient utilisation efficiency (kg kg^{-1})	60	286	48	434	548	618	1041
Nutrient uptake efficiency (kg kg^{-1})	0.67	0.28	0.57	0.04	0.19	0.03	0.02
Nutrient harvest index (%)	81	85	89	7	50	77	44
AUE (kg kg^{-1})	198	378	133	97	2718	154	

Improving NUE of potato plants is key in improving sustainability of production (Tiwari et al. 2018). The particular improvement of N use efficiency is key in reducing the adverse impact of N loss to the environment as well as financial implications toward producers (Fageria et al. 2008). Nutrient use efficiency refers to the DM production per unit of nutrient taken up by the plant. (Zebarth et al. 2004; Dobermann 2005; Abbasi et al. 2011; Hirose 2011; Weih et al. 2011; Gholipouri and Kandi 2012; Hu et al. 2014; Sapkota et al. 2014; Xu et al. 2015; Gitari et al. 2018; Jia et al. 2018; Tiwari et al. 2018). Change in NUE can be attributed to variation in the acquisition of the particular nutrient in question by the plant, referred to as nutrient uptake efficiency (NU_pE) as well as factors that influence the efficiency at which the crop utilises the absorbed nutrient, known as nutrient utilisation efficiency (NU_tE).

Nutrient use efficiency follows a similar trend to AUE. Results from this study (Table 4.18) indicated that NUE on average for all fields were in the general order Mg > P > N > K > Na > S > Ca. All fields, except Fields 8 and 9 (25.4 and 24.6 kg kg^{-1}, respectively), had a low Ca use efficiency, ranging from 9.6 to 15.5 kg kg^{-1} which can be attributed to the low mobility of the Ca ion within the soil and plant as well as large applications prior to planting in the form of gypsum. Magnesium use efficiency was high for the area (111 kg kg^{-1}) and is a result of the very low application of Mg in potato cropping systems. Fields 7 and 9 showed low Mg use efficiency (36.3 and 30.1 kg kg^{-1} respectively), which was caused by a higher presence of Mg in the irrigation water. Nutrient use efficiency generally increased with an increase in DM yield, which agrees with the findings of Gitari et al. (2018). However, a higher availability and application of nutrients can negatively affect NUE. This is clearly indicated by Fields 2 and 6, which obtained very similar DM yields (11.2 and 11.1 t ha^{-1}, respectively) (Table 4.18). Field 2 had a lower application of nutrients P, K, Mg and Na from fertiliser and water application than Field 6, resulting in a 26, 21, 6 and 60% higher P use efficiency, K use efficiency, Mg use efficiency and Na- use efficiency respectively. Field 6 had a lower application of N, Ca and S, resulting in 16, 16 and 28% higher N use efficiency, Ca use efficiency, and S use efficiency, respectively than Field 2. This indicates a lower efficiency when nutrient application is high, unless DM yield is increased.

Table 4.18 Nutrient use efficiency obtained for all monitored fields from earliest planted to latest planted.

Nutrient use efficiency (kg kg^{-1})							
Field	N	P	K	Ca	Mg	S	Na
Field 1	30.0	63.7	34.2	13.8	119.6	23.2	30.3
Field 2	33.8	88.1	23.9	13.0	140.0	16.2	51.1
Field 3	30.6	46.8	19.7	9.6	110.7	13.0	28.6
Field 4	42.4	64.0	27.0	13.6	112.3	18.9	22.8
Field 5	32.2	85.0	23.0	12.5	126.8	15.7	42.7
Field 6	40.1	70.2	19.8	15.5	132.7	22.6	20.3
Field 7	40.6	68.5	21.3	14.5	36.3	21.9	5.7
Field 8	83.9	123.9	52.9	25.4	155.7	34.4	26.8
Field 9	34.9	100.2	23.6	24.6	30.1	14.4	9.8

Nitrogen use efficiency observed ranged from 30.0 to 83.9 kg kg^{-1}, with a general increase with increasing DM yield. Potato is considered an N responsive crop (Tiwari et al. 2018) and N is particularly important for the accumulation and partitioning of DM throughout the plant. The importance of N in potato cropping systems is also illustrated by the N uptake efficiency (Table 4.19). An average N uptake efficiency of 0.67 kg kg^{-1} was obtained. The values in the present study are higher than the range (0.33 – 0.50 kg kg^{-1}) reported by Zvomuya et al. (2003). Gitari et al. (2018) reported N and P uptake efficiencies in Kenya ranging from 0.54 to 0.80 kg kg^{-1} and 0.22 to 0.30 kg kg^{-1} respectively, which are similar to the Sandveld results. Field 8 obtained an N uptake efficiency of 1.05 kg kg^{-1}. Therefore, the surplus of N uptake is assumed to be absorbed from the soil profile reserves, which is observed in the nutrient balance (Table 4.20).

Table 4.19. The nutrient uptake efficiency for each field monitored in the study.

Nutrient uptake efficiency (kg kg^{-1})							
Field	N	P	K	Ca	Mg	S	Na
Field 1	0.61	0.20	0.68	0.05	0.27	0.04	0.03
Field 2	0.74	0.32	0.47	0.03	0.27	0.03	0.04
Field 3	0.60	0.18	0.44	0.03	0.26	0.02	0.03
Field 4	0.55	0.20	0.51	0.03	0.19	0.03	0.02
Field 5	0.69	0.33	0.48	0.03	0.26	0.03	0.04
Field 6	0.62	0.25	0.39	0.04	0.25	0.04	0.02
Field 7	0.63	0.24	0.48	0.03	0.07	0.04	0.01
Field 8	1.05	0.41	1.22	0.03	0.19	0.04	0.02
Field 9	0.59	0.38	0.56	0.06	0.05	0.03	0.01

The K uptake efficiency for Field 8 showed a similar trend to N. A value larger than 1 was obtained (1.22 kg kg^{-1}), therefore 0.22 kg kg^{-1} of the K taken up by the plant was provided by a source other than fertiliser or water application and can then be presumed to have been provided by the soil (Table 4.22). The average uptake efficiency for K in the region was 0.57 kg kg^{-1}. These high values indicate the importance and efficiency with which the potato plant absorbs both N and K. Lower values for P, Ca, Mg, S and Na, 0.28, 0.04, 0.19, 0.03 and 0.02 kg kg^{-1}, respectively, were obtained in the study. Nutrients such as S and Na, however, are not required in large amounts by potato plants. The average results obtained in this study for NU_tE ranged from 60 to 1041 kg kg^{-1} (N and Na, respectively) (Table 4.17). The high Na utilisation efficiency is due to the small concentration of Na present within the plant; therefore, the utilisation of nutrients present in small concentrations is high and increases with an increasing DM yield. The same is observed for nutrients P, Ca, Mg and S (286, 434, 548 and 618 kg kg^{-1} respectively) However, potato plants require these nutrients in smaller quantities than N and K (refer to Table 4.12). The Sandveld region has a mean N utilisation efficiency and K utilisation efficiency of 60 and 48 kg kg^{-1} respectively. The lower values are accredited to the high presence of these nutrients in the plant due to a higher uptake efficiency and the requirement of these nutrients in larger concentrations than others, particularly during the vegetative growth stage.

Nutrient harvest Index refers to the ratio of tuber nutrient uptake to plant nutrient uptake. Since nutrients within the roots have little influence on nutrient partitioning within the potato plant, root nutrient content is assumed negligible. Nutrient harvest index is a parameter that indicates the partitioning and re-translocation of nutrients from aboveground vegetative parts to tuber growth and the efficiency at which the crop utilises the absorbed nutrients for tuber production. Different crops utilise nutrients differently. Lopez-Bellido et al. (2003) reported mean N harvest index values of 82% for faba bean (*Vicia faba*). Results in this study show that the mean N harvest index for potato crops in the Sandveld region was 81%, with the lowest value of 76% (Field 1) (Table 4.17). This indicates that potato is efficient at re-translocating N from the aboveground plant system to tubers. However, da Silva et al. (2018) produced lower results than obtained in the present study (81%), with an average N harvest index of 65% for potato production under differing irrigation methods, with sprinklers producing the highest N harvest index of between 66 to 70%. Zebarth et al. (2004) showed mean results of N harvest index at 69% for 20 cultivars grown in Canada, with rates of 100 kg ha^{-1} banded at planting. Fageria (2014) reported a relationship between grain harvest index and yield, however, no correlation between N harvest index and potato yield was observed in the present study. The N harvest index did not increase with an increase in utilisation efficiency of N, as was suggested by Fawcett and Frey (1983). The relationship between nutrient harvest index and the fertiliser rate and environment is reported to be very complex and varies among cultivars (Zebarth et al. 2004). However, nutrient harvest index is an important parameter that indicates the efficiency with which absorbed nutrients are translocated from the vegetative plant parts to the tuber. The mobility of an ion also plays a role in its re-translocation, as seen with Ca (7% Ca harvest index).

4.3.4 Nutrient balance

Nutrient balance calculations were conducted to estimate the residual nutrient content, which refers to the applied nutrients, left in the soil after harvest (to a depth of 1 m) or lost by runoff. Negative values indicate that more nutrients were taken up by the crop than was supplied through fertilisers and water application. It can be assumed that negative nutrient balances resulted from a supply of nutrients to the crop by the soil.

The N inputs and losses (Table 4.20) for Field 2 and 3 are balanced, with only 1.1 kg N ha^{-1} left in the soil and or lost as runoff and 0.2 kg N ha^{-1} taken up by the plant, in excess of nutrient and water application, from the soil, respectively. For Fields 5 and 9 large amounts of N application occurred from irrigation water, which resulted in an excess of N left in the profile or lost as runoff. Field 5 had a residual value of 69 kg N ha^{-1} and Field 9 102 kg N ha^{-1}. Field 2 also had a large application of N through irrigation water, however, substantial leaching occurred at 86 kg N ha^{-1}, in comparison to Fields 5 and 9 (34 and 44 kg N ha^{-1}, respectively). Field 8, on the other hand, mined substantial amounts of N from the soil profile (80 kg N ha^{-1}) as a result of large yields obtained.

Giletto and Echeverria (2013) reported residual soil N at harvest, ranging from 54.2 to 62.5 kg ha^{-1} to a depth of 60 cm in the soil profile. The same study reported that inputs of 299 kg N ha^{-1} resulted in N outputs of 235 kg ha^{-1}. The loss of N via plant removal and leaching was larger in the present study. Roy et al. (2001) indicated that at high fertiliser rates (150% of the recommended rate) resulted in positive nutrient balances. This was difficult to report on in the present study due to the application of similar fertiliser rates in the Sandveld. Therefore, the nutrient balance was mainly determined by leaching and plant nutrient removal rates. The results obtained in the Sandveld are consistent with those reported by Shepherd and Postma (2000) and Giletto and Echeverria (2013), who concluded that the amount of water drained and amount of N applied as fertiliser influenced the residual N remaining in the soil after harvest. Due to the long rotation period of potato crops, it can be assumed that the majority of the N left in the soil after harvest will be lost during the fallow periods.

Table 4.20. Nitrogen nutrient balance conducted for intensively monitored fields. Residual refers to the nutrients left in the soil after harvest or lost via runoff and plant nutrient removal includes both tuber and haulm nutrient removal.

			Nitrogen (kg ha^{-1})		
Field	Fertiliser	Water	Leached	Plant nutrient removal	Residual
Field 2	302	30	86	244	1.1
Field 3	294	0.0	118	176	-0.2
Field 5	302	34	34	233	69
Field 7	288	0.0	0	180	108
Field 8	294	0.0	66	308	-80
Field 9	302	51	44	207	102

The results showed substantial amounts of P left in the soil profiles or lost as runoff at the end of the crop seasons (Table 4.21). Field 3 was the only intensively monitored field where the crop used more P than was applied by fertiliser and water, with an excess of 1.5 kg P ha^{-1} having been taken up from the soil by the crop. However, contributing to the low P negative value was the substantial P leached of 160 kg ha^{-1}. All the other monitored fields where drainage was collected had positive residual values ranging from 17 to 101 kg P ha^{-1}. Field 8 had a large application of P through fertiliser and water with very little leached, hence the reason for the large amount of P left in the soil profile. The results indicate that large amounts of P are not used by the crop or lost, thus, potentially resulting in a build-up or runoff loss, as reported by Alva et al. (2011).

Table 4.21. Phosphorus nutrient balance conducted for intensively monitored fields. Residual refers to the nutrients left in the soil after harvest or lost via runoff and plant nutrient removal includes both tuber and haulm nutrient removal.

			Phosphorus (kg ha^{-1})		
Field	Fertiliser	Water	Leached	Plant nutrient removal	Residual
Field 2	125	1.5	11	41	76
Field 3	189	3.5	160	34	-1.5
Field 5	125	1.7	15	42	70
Field 7	167	4.1	0	41	129
Field 8	189	10.3	16	82	101
Field 9	118	4.9	60	46	17

Potassium was taken up by the crop in excess from the soil in very large quantities (Table 4.22) in Field 8 (374 kg K ha^{-1}), however, this was caused by the substantial removal of K from plant uptake (tuber and haulm) (567 kg K ha^{-1}) and the large levels leached (273 kg K ha^{-1}). The large mining of K by the crop in Field 8 indicates the availability of substantial K in the profile from previous crops. Fields 2 and 3 had similar nutrient inputs and losses, which resulted in similar K levels left in the soil profile or lost as runoff (80 and

95 kg K ha^{-1}, respectively). Fields 5 and 9 did not incur large levels of leached K below a 1 m depth, compared to the other monitored fields. However, Fields 5 and 9 had large applications of K onto the fields (from fertiliser and water), resulting in large amounts of K assumed to be left in the soil profile preceeding harvest.

Table 4.22. Potassium nutrient balance conducted for intensively monitored fields. Residual refers to the nutrients left in the soil after harvest or lost via runoff and plant nutrient removal includes both tuber and haulm nutrient removal.

			Potassium (kg ha^{-1})		
Field	Fertiliser	Water	Drainage	Plant nutrient removal	Residual
Field 2	459	8.9	166	222	80
Field 3	454	4.2	160	203	95
Field 5	459	10.3	17	224	228
Field 7	495	55.0	0	263	287
Field 8	454	12.2	273	567	-374
Field 9	443	80.0	76	292	154

There was a negative Ca and S balance (70 and 94 kg ha^{-1}) (Tables 4.23 and 4.24) in the profile of Field 9 due to no application of gypsum prior to cropping. Substantial amounts of Ca and S were left in the soil profile or lost as runoff for Fields 2, 3 and 5 after harvest as a result of pre-planting gypsum application. These amounts left in the soil profile ranged from 41 to 683 kg Ca ha^{-1} and 355 to 559 kg S ha^{-1}. Field 8, on the other hand, had large amounts of Ca and S inputs into the soil profile. However, a loss of 900 kg Ca ha^{-1} occurred, resulting in lower levels left in the soil or lost as runoff (41 kg Ca ha^{-1}). Sulphur was also leached in large amounts at 814 kg S ha^{-1}, resulting in the excess plant uptake of S from the soil profile of 126 kg S ha^{-1}. Magnesium was mined by the crops in Fields 2 and 8 (Table 4.25). A total of 35 and 44 kg Mg ha^{-1}, respectively, was likely obtained from the soil profiles. Plant nutrient removal was similar for all fields, ranging from 21 to 29 kg Mg ha^{-1}. Application of large amounts of Mg through fertilisers is not practiced in the region and ranged from 8 to 46 kg Mg ha^{-1}. However, Mg is present in large concentrations in irrigation water and hence the substantial application of Mg through irrigating is observed, which influenced the large leached rates obtained.

Table 4.23. Calcium nutrient balance conducted for intensively monitored fields. Residual refers to the nutrients left in the soil after harvest or lost via runoff and plant nutrient removal includes both tuber and haulm nutrient removal.

Calcium (kg ha^{-1})					
Field	Fertiliser	Water	Drainage	Plant nutrient removal	Residual
Field 2	841	18.5	268	28	564
Field 3	924	16.4	242	27	672
Field 5	841	21.4	152	28	683
Field 7	603	201.2	0	28	776
Field 8	924	47.7	900	31	41
Field 9	217	283.9	542	29	-70

Table 4.24. Sulphur nutrient balance conducted for intensively monitored fields. Residual refers to the nutrients left in the soil after harvest or lost via runoff and plant nutrient removal includes both tuber and haulm nutrient removal.

Sulphur (kg ha^{-1})					
Field	Fertiliser	Water	Drainage	Plant nutrient removal	Residual
Field 2	679	9.7	314	20	355
Field 3	677	13.8	170	17	504
Field 5	679	11.2	112	20	559
Field 7	433	102.0	0	19	516
Field 8	677	40.3	814	28	-126
Field 9	106	748.5	927	22	-94

Table 4.25. Magnesium nutrient balance conducted for intensively monitored fields. Residual refers to the nutrients left in the soil after harvest or lost via runoff and plant nutrient removal includes both tuber and haulm nutrient removal.

Magnesium (kg ha^{-1})					
Field	Fertiliser	Water	Drainage	Plant nutrient removal	Residual
Field 2	46	34.4	94	21	-35
Field 3	41	40.2	43	21	17
Field 5	46	39.8	38	22	26
Field 7	59	264.2		22	301
Field 8	41	117.3	173	29	-44
Field 9	8	401.0	332	22	55

Substantial positive nutrient balances obtained in this study indicate that in general, over application of nutrients in potato cropping systems is occurring in the Sandveld region. However, in certain cases (in fields that negative nutrient balances occurred) it was observed that a larger uptake of nutrients by crops, compared to what was applied through fertiliser and irrigation water took place. Abdul Mojid and Wyseure (2014) reported similar findings for N and K when fertiliser application did not meet the nutrient requirement of the crop. However, in the Sandveld, nutrient application was sufficient to meet crop nutrient removal, with the exception of Field 8 with regards to N and K. Field 8 produced substantial yields, which resulted in large plant nutrient removal. The negative nutrient balances reported in the present study arise from the high levels of nutrients lost by leaching below the root zone due to the low nutrient holding capacities of the sandy soils. Although, in the cases when less nutrients were applied than was taken up by the crop and lost by drainage, it indicates that nutrients are available in the soil from previous crops and adjustment of fertiliser applications to soil analysis may be a possible future strategy to prevent substantial nutrient losses. However, the extent at which nutrients are lost due to rainfall during fallow periods must be investigated. The large requirement of N and K is observed through the high levels of plant removal, followed by P. Calcium, Mg and S are removed in smaller and similar quantities. The large amounts of P, Ca and S, left in the soil after leaching and cropping can be ascribed to various factors. The low absorption and leaching of P (in most cases) is due to the lack of mobility within the soil profile and binding/precipitation with other ions. Calcium is reported as an immobile ion in soil and does not move through the profile easily, however, there is a great input of Ca and S into these systems and great losses by leaching occurred. The lack of uptake efficiency for Ca and S resulted in a build-up in soil profiles.

It is expected that residual values obtained in the study (Tables 4.20 to 4.25) should correspond with soil analyses results (Appendix II). A comparison was conducted; however, the agreement was poor. One possible explanation is that soil samples were conducted to a depth of 0 to 90 cm, therefore a large mass of soil was used. Thus, a small error (in sampling or nutrient analysis), may result in huge errors in the calculated nutrient amount (kg ha^{-1}) present in the soil. Another possible reason is that drainage was collected at a depth of 1 m and soil samples were only conducted to a depth of 90 cm. Therefore, the exclusion of 10 cm of soil occurred, which per ha and field contributed to a substantial amount of nutrients not accounted for in the soil analysis.

4.4 Tuber yield and size distribution

4.4.1 Tuber yield

Yield potentials calculated using the LINTUL DSS potato model (Haverkort et al. 2015) assume no abiotic or biotic limitations to crop growth. The results obtained varied from 46.2 t ha^{-1} for the early March planting to 89.9 t ha^{-1} for the late November planting. The highest actual yield obtained between the studied sites for the variety FL2108 and Sifra were 57.5 t ha^{-1} and 118.2 t ha^{-1}, respectively. The cultivar FL2108 used in the majority of the sites is not as high a yielding variety as Sifra. Yield potentials were lowest for the March plantings due to these crops growing mostly through the cloudy winter months, when available solar radiation was the most limiting factor to production. Yield potentials increased with later planting dates (May and June), as these crops grew into spring and early summer, when more solar radiation was available. Crops planted in July grew into the hot and dry summer months, which caused more heat stress, as seen for Field 7, in spite of more available radiation, resulting in a yield suppressing effect, which agrees with reports by Zhou et al. (2016) and Paul et al. (2016). However, summer planted crops (Fields 8 and 9) obtained 132 and 65% of the calculated yield potential, suggesting negligible negative effect of heat stress on the crops. This may at least partly be explained by the fact that crops were irrigated frequently with large amounts of water, which helped to cool the canopy down and thus created conditions conducive for growth. Field 9, due to its location close to the Atlantic Ocean, had a cooler microclimate caused by cool winds blowing from the cold ocean. However, often fog from the ocean blew over this field, resulting in a lowered yield potential due to less available solar radiation.

The actual yields achieved ranged from 34.7 t ha^{-1} (Field 1) to 118.2 t ha^{-1} (Field 8), which were 75 and 132% of the calculated potential yield, respectively. It is reported that high temperatures reduce the crop's photosynthetic capacity and increase respiration, resulting in reduced radiation use efficiency and thus, biomass accumulation (Haverkort et al. 2013). However, the cardinal temperatures affecting photosynthesis and radiation use efficiency as used by the LINTUL DSS potato model, penalises photosynthesis severely when hot temperatures occur. The radiation use efficiency of 2.5 g DM MJ^{-1} PAR used in the model, under optimal conditions, is perhaps also too low and needs to be reassessed (Personal Communication, AC Franke; unpublished data). Therefore, the fields producing yields higher than the potential yields (Fields 2 and 8) was a result of the model penalising photosynthesis at temperatures above 30 °C. Both Fields 2 and 8 obtained substantial periods of high temperatures (Appendix IIIa). It was also indicated that ET cooling leads to lower canopy temperatures compared to ambient temperatures, reducing the heat experienced by the crop during summer months and that the inclusion of ET cooling in the model may improve yield simulations (Personal Communication, AC Franke; unpublished data).

Actual yields higher than 66% of the yield potential are acceptable, while values above 75% can be considered good. Yield potential during the winter growing periods in the Sandveld is limited by less available solar radiation (Ierna 2009; Zhou et al. 2016). Tang et al. (2018) indicated a positive correlation between yield and total radiation during the growth period of potato crops in North China, which is in agreement with a study conducted in South Africa by Steyn et al. (2016). In spite of the wide range of yields recorded, actual yields for seven of the monitored fields were above 75% of the potential, which suggests that available resources were used efficiently. Fields 3 and 9 obtained an actual yield of 54 and 65% of the potential yield attainable, respectively. A number of factors can cause these low values. Field 3 received large amounts of rainfall and therefore, leaching of nutrients was high, resulting in less availability for uptake. Early crop development also occurred during cool temperatures and lack of solar radiation. Field 9, on the other hand, was planted in summer and received sufficient solar radiation, however, similarly to Field 3, temperatures were cool throughout crop growth. Substantial leaching also occurred in Field 9 due to over irrigation, potentially affecting yields negatively.

Table 4.26. Potato tuber yield, simulated potential tuber yield and the ratio of actual to potential yield for monitored Sandveld fields.

Type	Field	Tuber yield ($t\ ha^{-1}$)	Potential yield ($t\ ha^{-1}$)	Actual : potential yield
Intensive	Field 2	51.6	46.6	1.11
	Field 3	41.5	77.1	0.54
	Field 5	49.8	67.2	0.74
	Field 7	53.9	58.0	0.93
	Field 8	118.2	89.3	1.32
	Field 9	59.0	89.9	0.65
Extensive	Field 1	34.7	46.2	0.75
	Field 4	57.5	71.8	0.80
	Field 6	51.2	53.9	0.95

4.4.2 Tuber size distribution

Across all fields, 44.8% of the tubers were classified as medium and 30.7% as small (Figure 4.48). A maximum of 56.4% (Field 7) was observed for the medium classed tubers and a minimum of 26.8% (Field 5). Field 5 produced the highest proportion of tubers in the small class (60.1%), with Field 8 producing the lowest number of small tubers (8.4%). Only 66% of the fields under observation produced large tubers, with Fields 5, 3 and 1 producing no tubers in the large class. The highest proportion of large tubers observed for cultivar FL2108 was for Field 6 (6.0%). This high proportion of large tubers can be attributed to the clay layer producing a water table, resulting in an abundance of water and nutrient availability within the tuber zone during the bulking phase. In general, FL2108 is not a large tuber producing cultivar, which is preferred by the crisp processing industry. In comparison, the cultivar Sifra (Fields 8 and 9) produced 25.6 and 1.8% tubers classed as large, respectively. Overall Field 8 produced the better tuber size distribution. Field 1 was infected by late blight (*Phytophthora infestans*), which could have attributed to poor tuber bulking and development due to early senescence. The crop for this field was terminated early and the low total water and nutrient amounts applied will have resulted in smaller tubers developed. In contrast, Field 3 was observed as a healthy crop throughout growth, with the application of adequate water and nutrients. However, temperatures were low with an average of 15.9°C for the growth season. Walworth and Carling (2002) suggest that larger tubers are favoured by irrigation. However, the results obtained for Field 3 contradict this statement, as more than adequate amounts of water was available. The lack of large tuber production may have been influenced by the amount of drainage occurring due to an oversupply of water (rain and irrigation), resulting in nutrient leaching and a lack of sufficient available nutrients. The proportion of tubers classed as medium, medium-large and large was lowest for the March planted fields and increased for May and June as well as November and December plantings, with the exception of Field 7 (which was slightly under irrigated). The increase in the portion of larger tubers occurred with the increase in temperature and available solar radiation, which improved the plant's ability to utilise resources more efficiently due to an increased photosynthetic activity and production of assimilates. Therefore, the increase in tuber size distribution is directly correlated with an increase in yield.

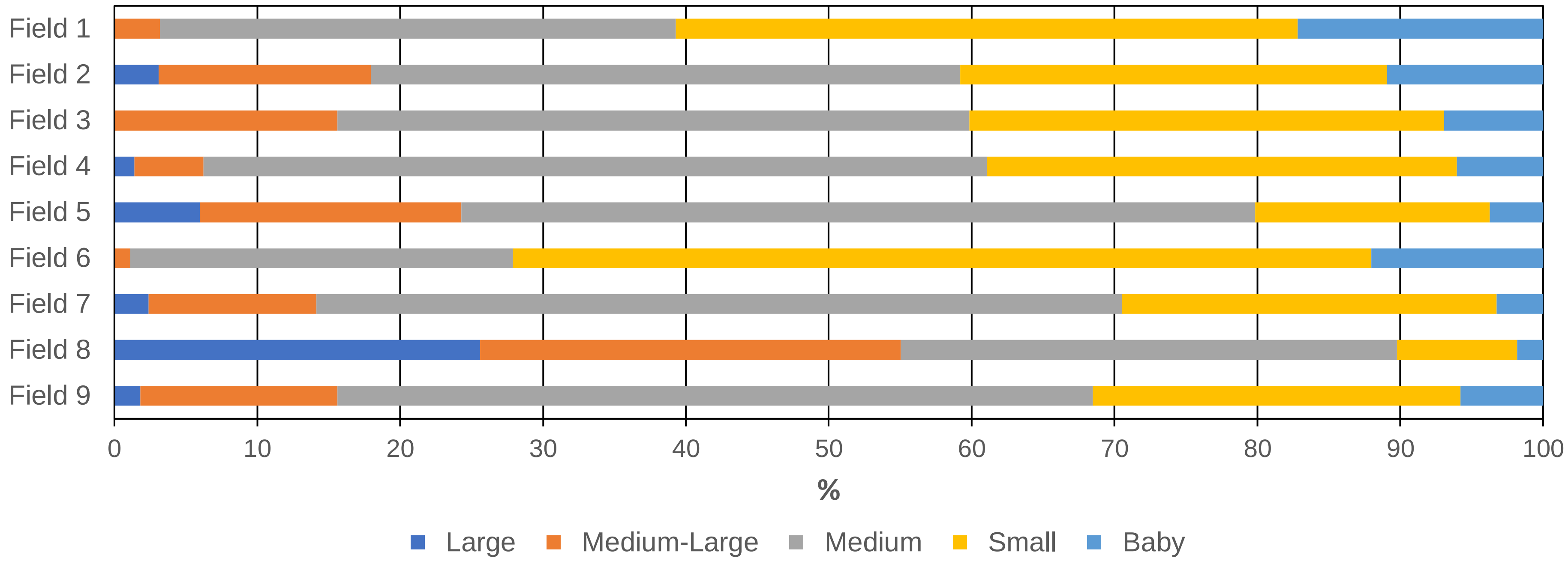

Figure 4.48. Size distribution of harvested tubers. From top to bottom is the earliest to latest planted fields. Rule for size classification: Baby (5-50g), Small (50-100g), Medium (90-170g), Medium-Large (150-250g), Large (>250g

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The aim of this study was to quantify inputs and losses occurring in potato production systems in the Sandveld region of the Western Cape. The study was conducted in order to close the gap in knowledge with regard to water and nutrient leaching under current management practices. The research did not look at altering management strategies to improve production, but investigated current potato cropping inputs and losses and through that, recommendations of how best to improve efficiencies along with further enhancements to the research can be made. The benefit of quantifying losses and system inefficiencies for producers will allow them to optimise production and reduce unnecessary input costs. Apart from agronomic and economic benefits for farmers of improved nutrient and water use efficiencies, the need to protect the fragile ecosystem present within the Sandveld region is also evident. Nutrient leaching into groundwater and water sources, as well as refining and preventing excessive waste of water, should be limited. By understanding the causes of drainage, crop evapotranspiration changes and climatic conditions throughout the growth cycle, management practices to optimise inputs and resource use efficiency can be recommended as well as future research requirements. To address these needs, the study was approached through four objectives:

1. *To assess the efficiency of irrigation systems with regards to water application in the Sandveld growing region.*
2. *To compare actual water application with simulated crop irrigation requirements and identify crop water needs for specific growing seasons to assess potential over- or under-irrigation.*
3. *To quantify drainage and assess the effect of irrigation water and rainfall on drainage accumulation and water use efficiency as well as to investigate methods of irrigation scheduling to improve efficient water use in the region.*
4. *To compare actual yields with simulated attainable yields and explore management strategies that can be implemented to increase nutrient use efficiency.*

The set objectives were addressed as follows in the study:

Objective 1: To assess the efficiency of irrigation systems with regards to water application in the Sandveld growing region.

The lack of knowledge regarding the efficiency of irrigation systems was indicated for the region. Irrigation systems are generally only evaluated during installation. Due to the harsh climatic conditions as well as brackish water used, it is notable that the irrigation structures and equipment deteriorate over time. Therefore, the need for repeated evaluations of centre-pivot efficiencies in the region is evident, as it is currently non-existent. The majority of the efficiency parameters evaluated were above the acceptable norms as provided within the literature (Clemmens and Dedrick 1994; Savva and Frenken 2002; Reinders 2013; Abd El-Wahed 2016). Efficiency parameter values for the application efficiency (AE), coefficient of uniformity (CU_{HH}) and distribution uniformity of the lowest quarter (DU_{lq}) ranged from 64 to 99%, 81 to 93% and 70 to 89%, respectively. There is, however, still room for improvement, which can be conducted through the periodic evaluation of irrigation systems (~ every one to two years) with the goal of improving parameters to > 90%. This should contribute to an increase in water use efficiency (WUE) and reduction in unnecessary water losses.

Fields 2, 6 and 8 produced application efficiency values below the acceptable norm (76, 77 and 64%, respectively) resulting in the need to over-irrigate by 24, 23 and 36%, respectively in order to apply the correct quantity of water. The low AE values caused the producer's perception of the amount of water being applied to vary from the actual irrigation application. This was clearly indicated for Field 6. The famer set the pivot to apply 10 mm of water per cycle when the actual application was 5.3 mm. The cause of poor AE is a result of various factors. Field 6 was observed to have a very low operating pressure (50 kPa) measured at the last pivot tower (normal operating pressures range from 70 to 500 kPa) and therefore, this contributed to the reduced application of water. On the other hand, Field 8 showed a low AE due to the large height of the spray nozzle heads from the crop surface, as well as the nozzles used, which produced fine droplets. Due to the windy conditions where the field was situated, the high nozzle heights and fine spray resulted in large water dispersion. A preventative measure is to drop the nozzle head heights closer to the crop and replace the spray nozzles with ones that produce larger droplets to reduce the effect of wind dispersion. Other efficiency parameters such as CU_{HH} and DU_{lq} were acceptable for all fields, with the exception of Fields 2 and 5, which were located on the same farm. The low CU_{HH} and DU_{lq} values resulted in the non-uniform application of water and water-soluble fertilisers throughout the field causing an uneven crop, affecting the yields negatively. The monitoring of the location of faulty nozzles was carried out during the system evaluation. Faulty nozzles should be replaced in order to correct and improve the distribution of water along the center-pivot boom.

Further to this is the recommendation to producers to monitor total water application during the season, which can be conducted satisfactorily with the use of electromagnetic flow meters or pressure transducers, as illustrated from the results. Pressure transducers are a more viable tool when cost is a factor, as it is an instrument that provides a cost saving of up to 75%, compared to flowmeters. The pressure transducers also gave an accurate measure of water application, with readings only varying from electromagnetic flow meters by 4.5 to 6.4% on average.

The overall improvement of irrigation system efficiencies and monitoring of water applications will cause an increase in the accuracy of applied water to meet the simulated crop water requirements, which is discussed in Objective 2 of the study.

Objective 2: To compare actual water application with simulated crop irrigation requirements and identify crop water needs for specific growing seasons to assess potential over- or under-irrigation.

From Objective 1 it was observed that actual irrigation application varied from that of the perceived amount being applied by the farmers. Generally, producers tend to over apply water in order to combat losses due to system inefficiencies and rapid water loss occurring from the sandy textured soil profiles. Therefore, with improved application efficiencies will come the need to match simulated crop water requirements to optimise water use efficiencies (WUE). Crop evapotranspiration (ET) for the studied Sandveld fields were quantified by developing basal crop coefficient curves for autumn, winter and summer planted fields. The need for the adjustment of standard FAO Kcb values was observed. Basal crop coefficient values used for 100% canopy cover until senescence [Kcb(mid)] were 3.7% higher than the standard FAO-56 values suggested by (Allen et al. 1998). The basal crop coefficient curve values used for the end of crop growth [Kcb(end)] were on average 9.5% higher than the FAO suggested value. This resulted in the under-estimation of crop water demands if standard FAO values are used for the Sandveld. That also iterates the need for specific field adjustments or seasonal adjustments as crops planted in autumn and summer reached 100% ground cover quicker and remained at full canopy cover for longer than crops planted in winter. This also indicates the need to alter irrigation application according to crop ET demand, which is not commonly practiced by growers in the region. The recommended [Kcb(ini)] values remain the same at 0.15 for the different planting periods, [Kcb(mid)] and [Kcb(end)] values suggested for the Sandveld region are shown in Table 5.1.

Table 5.1: Adjusted basal crop coefficient values for various planting periods, which can be used to create a basal crop coefficient curve to estimate crop water requirements for potatoes grown in the Sandveld region.

	Basal crop coefficient values	
	Kcb(mid)	Kcb(end)
Autumn planted	1.10	0.64
Winter planted	1.14	0.72
Summer planted	1.10	0.65

The suggested basal crop coefficient curves provided a better estimation of total seasonal ET, compared to that calculated using the soil water balance method and LINTUL DSS potato model.

The ET obtained from the basal crop coefficient curves ranged from 188 to 647 mm for the season. Crops planted in autumn had lower ET demand (188 – 266) than winter and summer planted crops (305 – 346 mm and >350 mm, respectively). The basal crop coefficient values slightly under-estimated ET, due to the underestimation of the evaporative component (E). However, the ET(Kcb) estimations were a more realistic reflection of regional crop ET. The ET simulated using soil water balances (SWB) over-estimated crop water requirements, due to the runoff being assumed negligible during calculations, which was not always the case, as observed in Fields 2 and 5. The LINTUL DSS model also provided a good estimation of crop ET, however, errors occurred if the crop was allowed to die off naturally, and the assumption is made that ET during the second half of the season declines linearly, which is not the case, as was illustrated by Eddy covariance measurements (Personal Communication, AC Franke; unpublished data). Therefore, it is evident that adjusted Kcb curves can be a useful tool for irrigation scheduling in the Sandveld region. Further investigation into the ET(SWB) and the effect of runoff on ET estimation is required as well as the adjustment of the LINTUL DSS model to account for the non-linear decrease in ET during the second half of the season.

Various studies have been conducted on different irrigaiton strategies in potato cropping systems in order to optimise water management and improve WUE (Kashyap and Panda 2003; Yuan et al. 2003; Badr et al. 2012). The alteration of irrigation to crop physiological demands has indicated that the sensitive stages to water requirements are the vegetative and ripening stages (Fabeiro et al. 2001). Stalham and Allen (2004) suggested that partial deficit irrigation techniques do not affect overall plant growth. Carli et al. (2014) indicated the potential to increase WUE when decreasing water application after tuberisation, which had a limited effect on tuber yield. Alenazi et al. (2016) indicated the ability to increase WUE by applying 75% of the crop ET at the tuber bulking stage, without a negative influence on yield, in an arid region of Saudi Arabia. Other studies have however, indicated decreased yields due to deficit irrigation (Alva 2004; Badr et al. 2012). However, due to the rapid depletion of water from the very sandy soil profiles in the Sandveld growing area, farmers have limited opportunity to employ most of the above strategies, since the soils hold so little water, which means they can also not leave substantial room for rainfall in the profile.

One of the few strategies available to Sandveld growers is to match irrigation with crop water requirements during different growth stages. Currently irrigation is not altered according to crop needs in most cases, resulting in an over application of water, particularly during winter grown crops due to the effect that rainfall has on the increased potential of drainage to occur. The need to evaluate the effect of rainfall and over irrigation on drainage and quantifying the amount of drainage occurring in Sandveld potato fields was assessed in Objective 3.

Objective 3: To quantify drainage and assess the effect of irrigation water and rainfall on drainage accumulation and water use efficiency as well as to investigate methods of irrigation scheduling to improve efficient water use in the region.

Water application through irrigation in winter-grown periods ranged from 260 to 582 mm and was dependent on rainfall occurrence. With the inclusion of rainfall, winter-grown crops in 2018 received total water inputs for the season ranging from 531 to 744 mm. The actual water application was therefore, substantially larger than the irrigation requirement (IR) which was calculated using the ET demand as discussed in Objective 2 and the AE of irrigation systems as discussed in Objective 1. It was clearly observed that high water inputs through irrigation and rainfall during periods of low ET demand, resulted in an increase in drainage accumulation. Drainage amounts during winter periods ranged from 4 to 296 mm. The application of pre-planting irrigation contributed to the quicker saturation of soil profiles. This was clearly observed for Field 7, which had a dry sub-soil profile at planting. The field applied similar irrigation amounts to Field 2, however, it received 71 mm of rainfall compared to 486 mm. The drier soil profile contributed to the lack of drainage collected (4 mm) as well as good WUE was measured and hence, may be a strategy to consider for producers and future research.

Summer grown fields, on the other hand, produced large amounts of drainage due to the practice of high frequency irrigation during this period as a result of high temperatures and wind speeds during the summer months. Due to higher average temperatures, the emergence of above-ground potato growth occurs rapidly (7 – 14 days from planting to emergence). Therefore, this results in the profile still containing significant water from pre-planting irrigation applications. The wet soil profile, along with large water inputs (648 and 913 mm) and high irrigation frequency and amounts resulted in profile saturation and large amounts of drainage occurring (233 – 302 mm, respectively).

An average WUE of 85 kg mm^{-1} was obtained in the study. This average lies above the acceptable norm, which ranges from 75 to 80 kg mm^{-1} (Steyn et al. 2016), with winter grown crops obtaining 79.5 kg mm^{-1} and summer grown 104.2 kg mm^{-1}. The reason for lower WUE obtained during winter periods results from the lower yield potential due to a lack of available solar radiation and increased disease pressure (Field 1). Large rainfall events occurring during winter also give rise to substantial drainage accumulation for some of the fields, contributing to a low WUE. All fields with WUE values lower than the acceptable norm received substantial rainfall (between 143 and 271 mm) during the cropping season. When excluding rainfall, IWUE values indicated a higher efficiency, ranging from 88 to 134 kg mm^{-1}. However, the effect of rainfall cannot be ignored due to its large impact on leaching. Summer grown crops produced larger WUE values (86.2 and 122.2 kg mm^{-1}). The higher average temperatures, increased solar radiation and the lack of (or much less) rainfall contribute to an increased WUE as conditions were more conducive for increased yields than winter grown crops. The need for over application of water in order to combat the build-up of salts from the use of brackish irrigation water was mentioned by growers. This should be studied further, although only summer planted crops showed a tendency of drainage having higher EC levels (>170 mS m^{-1}) for long periods. This was caused by the high frequency of irrigation and lack of rainfall associated with the time of year. The leachate for winter grown fields generally remained at lower EC levels due to substantial rainfall occurring, which resulted in the natural leaching of salts out of the profile. The leaching requirement calculated for the year was low, ranging from 0.04 to 0.27. However, irrigation water sources were only measured once for each field and, due to farmers using various water sources, is subject to variation throughout the cropping season. Hence, constant measurement of the water source EC is recommended for future research. It is evident that due to the crop rotation of potato systems (one-year cropping, four to six years fallow) the need for leaching is negligible, as natural leaching will occur during winter periods when fields are fallow.

Farmers in the region did not have any form of device or tool to measure / assess soil water content, while a few were seen to dig soil pits once a week or every two weeks to observe the wetness of the soil. Generally, irrigation took place according to past experiences. Weather station data provided good information regarding the potential occurrence of drainage events and is recommended as an indicator. The use of basal crop coefficient curves for different planting times (autumn, winter and spring) in combination with ET_o (available from local weather stations) gave a good indication of actuall crop ET. This technique can, therefore, be recommended for producers in the area to obtain an indication of crop water demands

(Objective 2). Although using the adjusted basal crop coefficient curves may cause a slight under-estimate of ET, as the actual evaporation occurring during the early stages of crop development is unknown, this method will be a more accurate measure of ET, compared to current practices. A potential strategy for producers to also use, is to irrigate according to canopy cover, which can be estimated with the eye or calculated using a 1 m^2 grid. The canopy cover factor can then be multiplied by the reference ET (ET_o) obtained by a nearby weather station, to give a good estimation of ET. Soil probes, such as capacitance probes, gave a good indication of soil-water movement within the profile and can be recommended as an irrigation management tool. Although, due to the mountainous topography, data collection via telemetry was incomplete for a lot of the studied fields, the use of hand-held dataloggers for DFM probes is advised. The movement of water indicated by the probes also gave an indication of when drainage accumulation will occur, as peaks in soil water content as indicated by the DFM graphical illustrations, coincided well with drainage collection. Decagon probes were the more accurate measure of volumetric soil water content. However, the probes are less practical for commercial use as readings must be periodically downloaded with a laptop in the field, batteries need changing every fortnight and the cost of equipment is substantial in comparison with DFM probes. Chameleon sensors, on the other hand, were not good indicators of the soil water content in these sandy soils. Sensors did not correlate well with the Decagon and DFM probes as readings within the same fields gave different values and often suggested saturated conditions throughout the season when soil water content was suggested otherwise by the DFM or Decagon probes. Hence, Chameleon sensors are not suggested for use as irrigation scheduling tools within the Sandveld. The very sandy soil texture results in the inability of the Chameleon sensors to equilibrate with the soil profile due to the low unsaturated hydraulic conductivity of the sand.

It was clear that nutrient leaching was directly correlated with the drainage of water. As drainage increased, so did the increase in the amount of nutrients lost below the effective root zone of potato crops [~30 cm; Opena and Porter (1999)]. This was particularly notable when large rainfall events or over-irrigation occurred. The wide use of water-soluble fertiliser products in the area contributed to the high levels of nutrient leaching recorded. The alteration of irrigation management to rainfall events was observed for winter-grown crops, but due to the application of water-soluble fertilisers through '*high-tech fertigation*', also took place on days when substantial rainfall occurred or days preceding rainfall events. This contributed to the saturation of soil profiles, drainage as well as the loss of nutrients during winter periods. The need for a combination of water-soluble, less water-soluble and slow release fertilisers should be evaluated as a potential mitigation strategy for alleviating large nutrient losses. It was observed that large losses of Ca and S occurred due to the general practice of pre-plant gypsum applications in the region. This resulted in a mean loss of 421 kg Ca ha^{-1} and 467 kg S ha^{-1} through drainage below a 1 m depth of the soil profile. Sodium and Mg were also leached at high levels due to these elements being present in large quantities in the irrigation water sources (472 and 136 kg ha^{-1}, respectively). The large amount of P leaching, with an average of 52 kg P ha^{-1} and a maximum of 160 kg P ha^{-1} leached, was unexpected. However, this is attributed to the high P levels measured in the soil during equipment installation (Appendix II). On average, 70 kg N ha^{-1} and 138 kg K ha^{-1}, were leached. However, high levels of the applied N and K was absorbed by the crop (0.67 kg N and 0.57 kg K taken up per kg applied). The effect of nutrient application and losses on nutrient use efficiency is, therefore, evident and addressed in Objective 4.

Objective 4: To compare actual yields with simulated attainable yields and explore management strategies that can be implemented to increase nutrient use efficiency.

Seven of the nine monitored fields produced actual yields >75% of the potential yield, as calculated by the LINTUL DSS potato model, indicating the general efficient use of resources in the region. A major limitation to the attainable yield was the amount of solar radiation during the growth period as well as the heat factor. During winter periods, less solar radiation is available in comparison to summer months, hence yield potential for summer months is higher. However, crops that grew into hot, drier months had an increased possibility to incur heat stress, which had a potentially negative effect on yields.

Nutrient use efficiency generally increased with an increase in dry matter (DM) accumulation, however, it was negatively affected by high applications of nutrients. Fertiliser practices in the region were similar, with a mean application of 288 kg N ha^{-1}, 153 kg P ha^{-1} and 440 kg K ha^{-1}. Maximum application was 302, 189 and 522 kg ha^{-1} (N, P and K, respectively) and minimum 240, 118 and 217 kg ha^{-1} (N, P and K). The minimum application, however, occurred for Field 1, which was infected by late blight (*Phytophthora infestans*) towards the end of the season, and hence, the crop was terminated early. Fields 2 and 6 clearly indicated the effect of nutrient application on nutrient use efficiency, as both fields obtained similar DM yields. The nutrients applied in lower amounts resulted in an increase in nutrient use efficiency. Due to the similar fertilisation practices, changes in nutrient use efficiency were mainly a result of variation in DM production for the different fields. Fields with high DM production (Fields 4 and 8) produced good nutrient use efficiency values. All fields, with the exception of Field 9, obtained excellent Mg use efficiency. This is attributed to by Mg not being applied in large quantities in these potato production systems. The Mg applied was a result of irrigation water and hence, the reason for Field 9 having a low Mg use efficiency. Calcium and S had low use efficiency values due to the application of gypsum and S containing products early in the season. The nutrient use efficiency of various elements is also a result of the uptake efficiency of nutrients by the plant. The nutrients with low nutrient use efficiencies, except P, were absorbed at lower rates by the potato crop, as illustrated by the nutrient uptake efficiency. Potato crops are large users of N and K and hence, the reason for good N use efficiency and K use efficiency values ranging from 30 to 83.9 and 19.7 to 52.9 kg kg^{-1}, respectively. The P use efficiency values obtained in the study ranged from 46.8 to 123.9 kg kg^{-1}, but P uptake efficiency was low on average in the region (28%). This is due to P being applied at lower rates than other nutrients. It is therefore, clear that a decrease in nutrient supply while maintaining or improving yields is a potential strategy relevant for low fertile soils such as those present within the Sandveld region. Conversely, nutrient use efficiency (NUE) can be improved through an increased application of fertilisers. However, an increase in yield must occur. The amount of leaching observed in the study suggests a decrease in nutrient application to be the more ideal approach, as large amounts of applied nutrients are not absorbed by the plant and are lost through drainage below the effective rooting depth of potato cropping systems. Sandveld producers do not alter nutrient fertiliser rates according to soil analysis results. Often commercial farmers have a standardised regime for the majority of the fields located on a farm. The reduction in nutrient level to balance those present within the soil profile is recommended as a possible strategy to overcome high levels of nutrient leaching from soils in the Sandveld region and to optimise NUE. Large residual values obtained by nutrient balances indicated that large amounts of nutrients are left in the soil profile after harvest. It is also evident from negative nutrient balances that it cannot be assumed there are no nutrients in the soil profiles available prior to planting. This, along with the large levels of applied nutrients left in the soils indicated by positive nutrient balances (on average 85 kg P ha^{-1}, 530 kg Ca ha^{-1} and 349 kg S ha^{-1}) after harvest, may be used by a follow-up crop or result in reduced fertiliser need for the next potato cropping season and requires further investigation. However, it indicates the need to reassess fertiliser application rates required in potato cropping systems in the Sandveld region.

General conclusion

Drainage accumulation is a result of substantial rainfall during winter-grown crops and over application through high irrigation frequencies and applications in summer planted fields. Nutrient leaching is directly correlated with increased drainage. The need to evaluate centre-pivot irrigation system efficiencies and further investigate the alteration of irrigation management according to crop growth stages is evident, as well as the reassessment of current fertiliser application rates and products used to increase nutrient use efficiencies.

Limitations of this research study

There were various limitations noted during the study:

Soil samples were collected during equipment installation, which was after pre-planting fertilisation took place. Therefore, nutrients present in the analysis were not a true representation of pre-planting soil conditions. However, all of the pre-planting fertilisation was accounted for when looking at the soil analysis results and assumed to be present. The fertiliser application was deducted from soil analysis results in order to obtain a more accurate estimation of nutrients within the soil prior to planting. Soil bulk density values were used from soil samples sent to the laboratory for analyses. This was not representative of the true bulk density of the field. However, values were similar between the fields and for the two separate sampling periods (during equipment installation and yield analysis).

Concerning the soil-water balance, runoff was assumed negligible. However, it was observed in certain fields that runoff may have occurred, particularly in sloped fields along wheel tracks. Water balances were conducted in order to measure inputs and outputs against each other to observe if substantial losses may have occurred. There were no large errors in measurement indicated.

The destructive nature of installing the drainage lysimeter affected a large area within the field. It would be recommended looking into the use of an auger the size and depth of the lysimeter to disturb less of the surrounding profile. However, in this study the best practices that could be conducted with the equipment provided were carried out. Care was taken to ensure that soil was placed back into the profile as it was removed and tubers were planted with the same in-row spacing and depth as initial conditions.

The dry matter percentages for the variety FL2108 were calculated using specific gravity and converted using tables (Haverkort 2018). This may not be a true representation of the DM % as it is cultivar dependent. However, results were similar (slightly lower) to the DM measured for Field 8 and 9 for Sifra, which is what was expected. A standard specific gravity value of 1.083 for the variety FL2108 was assumed due to errors that occurred in the measurement procedure, due to the lack of specialised equipment available. Hence, the average values provided by Simba Ltd for the variety FL2108 over a wide range of fields and planting dates in the Sandveld for 2018 was used.

The importance of haulm nutrient removal was noted too late in the study. Therefore, this was only carried out for Fields 8 and 9. Results for both fields were similar and hence, the average of nutrients removed by the haulm in both fields was used. However, this may not be representative of the variety FL2108 as both Fields 8 and 9 were planted to the cultivar Sifra.

Recommendations for future research

The effect of irrigation system efficiencies should be further assessed with regards to correcting inefficient parameters and evaluating the effect of corrections on WUE. For example, the height of the sprinkler heads for Field 8 should be evaluated and the effect it may have on increased AE. Increased application efficiency along with the alteration of irrigation scheduling according to the basal crop coefficient curves should be evaluated and the effect that this method of estimating ET may have on yield and WUE in the Sandveld region should be investigated. Using an ET estimation method alongside the use of soil capacitance probes to schedule irrigation should be researched together with the variation of lower limits of water depletion that are permitted before water is applied and this should be assessed in the context of its impact on WUE.

Together with the monitoring of water application to reduce drainage and nutrient leaching there is a need to assess the use of water-soluble, less water-soluble and slow release fertiliser products during winter periods to alleviate large nutrient leaching losses occurring due to substantial rainfall events. The use of less water-soluble fertilisers may result in decreased leaching of nutrients due to a slower release. The practicality of applying fertilisers in a solid form rather than through irrigation water can be placed under scrutiny as certain farmers indicated that currently used broadcasters had varying spreading distances to the distances chemical spray booms used. Therefore, the purchasing of new equipment to standardise spray roads would need to be undertaken. The application of fertilisers will better be understood with the reassessment of the nutrient uptake curve for potato crops in the Sandveld region during autumn, winter and summer planted crops to observe the need of different nutrients at various stages. This may help optimise fertiliser regimes for specific cropping seasons in the area. The effect of nutrient leaching due to rainfall and over application of nutrients, may be alleviated by the use of deep rooting cover crops immediately after potato production. This is currently being conducted in other parts of South Africa (Personal Communication, JM Steyn; unpublished data), but it will be beneficial to observe the impact this may have in the Sandveld. The study on the effects that a deep rooting cover crop would have on nutrient absorption may prevent groundwater contamination. Furthermore, the understanding of the movement of nutrients in soil profiles within the Sandveld during fallow periods could give an indication of the movement of nutrients post crop growth as well as the effect that winter rainfall may have on nutrients when a crop is not grown or the field is under natural vegetation. The monitoring of nutrient levels in groundwater sources after crop growth should be conducted and will better aid the understanding of the environmental impact that potato production may have in the region. The monitoring of salts in the soil as well as the periodic evaluation of irrigation water quality throughout the season will also give a clearer indication of whether there is a need for water application to leach excess salts and the alteration of water salinity throughout the growth periods. With all of these suggested studies, it will be necessary to quantify the cost and economics of growing potatoes with regard to potential savings by preventing excessive nutrient leaching and improving WUE.

The use of hydrogels as soil conditioners has been studied extensively (Agaba et al. 2011; Demitri et al. 2013; Guilherme et al. 2015). The main advantage of the use of hydrogels as soil conditioners is the ability to control the release of stored water as the soil dries. Hydrogel is able to absorb significant amounts of water by swelling and retaining the water (and nutrients) within its structure (Fredric 1994). The ability of hydrogels to increase WUE has been indicated by Narjary et al. (2013) due to their ability to absorb up to 500 to 600 times their weight. Bhardwaj et al. (2007) concluded that mixing super absorbents (cross-linked polyacrylamides) with sandy soils may decrease rates of water drainage and increase availability of water and nutrients to crops. There have, however, been inconsistent reports in the literature regarding benefits for crop growth (Ingram and Yeager 1987; Viero et al. 2002; Green et al. 2004; Rowe et al. 2005). Abd El-Rehim (2006) indicated increased performance in faba bean (*Vicia faba*) production when using hydrogels as a soil conditioner. On the other hand, Green et al. (2004) concluded that the application of hydrogels did not sustain yields under reduced irrigation in the production of two bean cultivars in Colorado.

The use of hydrogels as soil conditioners within potato production systems in the Sandveld region should be assessed as a potential strategy to alleviate significant water and nutrient losses as well as improve water and nutrient use efficiencies.

CHAPTER 6: REFERENCES

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APPENDIX I

Appendix I. Weekly fertiliser applications (kg ha^{-1}) practiced in the Sandveld region. Week 0 refers to the pre-planting and pre-emergence nutrient applications, including the broadcasting of gypsum. Week 1 refers to the 1st week after crop emergence.

Field 1 fertiliser application kg ha^{-1}						
Week	N	P	K	Ca	Mg	S
0	41	96	63	440	0	296
1	39	6	14	2	1	0
2	39	6	14	2	1	0
3	39	6	14	2	1	0
4	29	6	18	2	1	0
5	23	0	18	2	1	0
6	9	0	18	2	1	0
7	6	0	18	0	0	0
8	6	0	18	0	0	0
9	7	0	14	2	0	0
10	4	0	7	1	0	0
Total	**240**	**118**	**217**	**457**	**6**	**296**

Field 2 fertiliser application kg ha^{-1}						
Week	N	P	K	Ca	Mg	S
0	44	46	116	752	29	622
1	26	4	26	0	1	1
2	26	4	26	0	1	1
3	27	27	27	35	3	25
4	27	4	24	18	1	0
5	18	6	36	0	2	5
6	27	4	24	18	1	0
7	18	6	36	0	2	5
8	27	4	24	18	1	0
9	15	5	30	0	1	5
10	15	5	30	0	1	5
11	15	5	30	0	1	5
12	15	5	30	0	1	5
Total	302	125	459	841	46	679

Field 3 fertiliser application kg ha^{-1}						
Week	N	P	K	Ca	Mg	S
0	56	134	138	867	25	677
1	23	5	23	0	1	0
2	23	5	23	0	1	0
3	23	5	23	0	1	0
4	28	4	24	19	1	0
5	17	6	34	0	2	0
6	28	4	24	19	1	0
7	17	6	34	0	2	0
8	28	4	24	19	1	0
9	14	5	27	0	1	0
10	14	5	27	0	1	0
11	14	5	27	0	1	0
12	14	5	27	0	1	0
Total	**294**	**189**	**454**	**924**	**41**	**677**

Field 4 fertiliser application kg ha^{-1}						
Week	N	P	K	Ca	Mg	S
0	56	134	138	831	25	635
1	23	5	23	0	1	0
2	23	5	23	0	1	0
3	23	5	23	0	1	0
4	28	4	24	19	1	0
5	17	6	34	0	2	0
6	28	4	24	19	1	0
7	17	6	34	0	2	0
8	28	4	24	19	1	0
9	14	5	27	0	1	0
10	14	5	27	0	1	0
11	14	5	27	0	1	0
12	14	5	27	0	1	0
Total	**294**	**189**	**454**	**888**	**41**	**635**

Field 5 fertiliser application kg ha^{-1}						
Week	N	P	K	Ca	Mg	S
0	44	46	116	752	29	622
1	26	4	26	0	1	1
2	26	4	26	0	1	1
3	27	27	27	35	3	25
4	27	4	24	18	1	0
5	18	6	36	0	2	5
6	27	4	24	18	1	0
7	18	6	36	0	2	5
8	27	4	24	18	1	0
9	15	5	30	0	1	5
10	15	5	30	0	1	5
11	15	5	30	0	1	5
12	15	5	30	0	1	5
Total	302	125	459	841	46	679

Field 6 fertiliser application kg ha^{-1}						
Week	N	P	K	Ca	Mg	S
0	33	65	33	556	0	391
1	31	5	25	2	1	0
2	34	27	25	29	3	18
3	29	4	32	19	3	0
4	29	5	45	14	3	0
5	23	26	76	31	3	32
6	23	5	45	7	3	0
7	23	5	76	7	3	14
8	23	5	45	7	3	0
9	14	5	76	0	0	14
10	14	5	45	0	0	0
11	0	0	0	0	0	0
Total	**277**	**156**	**522**	**671**	**24**	**468**

Field 7 fertiliser application kg ha^{-1}						
Week	N	P	K	Ca	Mg	S
0	42	116	42	566	47	415
1	22	7	37	0	0	0
2	32	7	48	9	3	5
3	22	7	37	0	0	
4	32	7	48	9	3	5
5	22	7	37	0	0	0
6	32	7	48	9	3	5
7	22	7	37	0	0	0
8	23	0	49	9	3	5
9	20	0	57	0	0	0
10	20	0	57	0	0	0
Total	**288**	**167**	**495**	**603**	**59**	**433**

Field 8 fertiliser application kg ha^{-1}						
Week	N	P	K	Ca	Mg	S
0	56	134	138	867	25	677
1	23	5	23	0	1	0
2	23	5	23	0	1	0
3	23	5	23	0	1	0
4	28	4	24	19	1	0
5	17	6	34	0	2	0
6	28	4	24	19	1	0
7	17	6	34	0	2	0
8	28	4	24	19	1	0
9	14	5	27	0	1	0
10	14	5	27	0	1	0
11	14	5	27	0	1	0
12	14	5	27	0	1	0
Total	**294**	**189**	**454**	**924**	**41**	**677**

Field 9 fertiliser application kg ha^{-1}						
Week	N	P	K	Ca	Mg	S
0	35	96	63	202	0	106
1	39	6	38	2	1	0
2	39	6	38	2	1	0
3	39	6	38	2	1	0
4	39	6	38	2	1	0
5	37	0	38	2	1	0
6	16	0	38	2	1	0
7	16	0	38	2	1	0
8	16	0	38	2	1	0
9	13	0	38	0	0	0
10	13	0	38	0	0	0
Total	**302**	**118**	**443**	**217**	**8**	**106**

APPENDIX II

Appendix II. Nutrient analysis results conducted from a depth of 0 – 90 cm at 30 cm intervals. Pre-planting analysis was conducted during equipment installation and therefore, fertiliser application prior to installation dates will be reflected in the analysis. Post-harvest analysis was conducted during yield analysis at the end of crop growth. Field 1 has missing pre-planting soil analysis results.

Field 1									
Sampling period	**Depth**	**pH**	**P**	**K**	**Ca**	**Mg**	**S**	**Na**	**Bulk density**
	cm	**KCl**			**mg kg^{-1}**				**g cm^{-3}**
	0-30	6.4	38.3	29.3	121.8	10.5	2.7	4.0	1.54
Post-harvest	30-60	5.8	32.5	23.0	103.0	8.0	1.2	3.8	1.46
	60-90	5.1	33.8	14.3	85.8	6.5	1.4	5.0	1.48
Average		**5.8**	**34.8**	**22.2**	**103.5**	**8.3**	**1.8**	**4.3**	**1.49**

Field 2									
Sampling period	**Depth**	**pH**	**P**	**K**	**Ca**	**Mg**	**S**	**Na**	**Bulk density**
	cm	**KCl**			**mg kg^{-1}**				**g cm^{-3}**
	0-30	4.4	65.8	33.3	164.3	18.8	11.1	20.3	1.51
Pre-planting	30-60	4.2	63.8	25.5	115.5	21.0	5.7	18.3	1.49
	60-90	4.1	37.0	17.3	91.0	14.5	5.6	18.8	1.49
Average		**4.25**	**55.50**	**25.33**	**123.58**	**18.08**	**7.47**	**19.08**	**1.50**
	0-30	4.3	72.3	38.0	156.3	22.8	3.8	12.8	1.41
Post-harvest	30-60	3.9	68.5	23.0	107.5	12.0	1.6	7.5	1.44
	60-90	4.0	39.0	15.8	96.3	10.8	1.9	6.3	1.47
Average		**4.07**	**59.92**	**25.58**	**120.00**	**15.17**	**2.42**	**8.83**	**1.44**

Field 3									
Sampling period	**Depth**	**pH**	**P**	**K**	**Ca**	**Mg**	**S**	**Na**	**Bulk density**
	cm	**KCl**	**mg kg^{-1}**						**g cm^{-3}**
	0-30	4.8	23.5	18.0	178.3	15.5	13.0	14.0	1.56
Pre-planting	30-60	4.4	16.5	12.0	108.8	9.0	5.7	11.8	1.59
	60-90	4.8	12.0	11.5	96.0	9.3	5.2	11.0	1.60
Average		**4.7**	**17.3**	**13.83**	**127.7**	**11.3**	**7.9**	**12.3**	**1.58**
	0-30	5.2	19.8	27.8	135.0	11.3	7.2	11.3	1.64
Post-harvest	30-60	5.0	15.5	22.8	128.5	10.8	5.1	11.8	1.64
	60-90	4.9	13.3	19.5	115.8	9.0	4.3	11.3	1.65
Average		**5.1**	**16.2**	**23.3**	**126.4**	**10.3**	**5.5**	**11.4**	**1.65**

Field 4									
Sampling period	**Depth**	**pH**	**P**	**K**	**Ca**	**Mg**	**S**	**Na**	**Bulk density**
	cm	**KCl**	**mg kg^{-1}**						**g cm^{-3}**
	0-30	5.0	38.0	26.3	220.5	13.0	20.4	9.5	1.56
Pre-planting	30-60	4.5	26.0	14.3	143.0	10.8	6.8	9.5	1.51
	60-90	4.7	14.8	10.3	134.3	11.8	4.4	10.3	1.54
Average		**4.7**	**26.3**	**16.9**	**165.9**	**11.8**	**10.5**	**9.8**	**1.54**
	0-30	5.5	29.8	19.5	163.5	16.5	8.3	24.3	1.63
Post-harvest	30-60	4.9	20.3	12.3	134.0	17.0	4.5	21.5	1.54
	60-90	4.9	15.0	11.0	127.8	16.8	3.4	17.3	1.55
Average		**5.1**	**21.7**	**14.3**	**141.8**	**16.8**	**5.4**	**21.0**	**1.57**

Field 5									
Sampling period	**Depth**	**pH**	**P**	**K**	**Ca**	**Mg**	**S**	**Na**	**Bulk density**
	cm	**KCl**			**mg kg^{-1}**				**g cm^{-3}**
	0-30	4.2	84.5	31.3	147.3	18.3	7.2	15.3	1.37
Pre-planting	30-60	3.9	84.8	19.3	109.0	12.5	5.1	13.0	1.37
	60-90	3.9	66.3	16.3	86.3	11.3	3.7	11.0	1.38
Average		**4.0**	**78.5**	**22.3**	**114.2**	**14.0**	**5.3**	**13.1**	**1.37**
	0-30	4.4	100.0	39.5	151.0	22.5	6.3	37.5	1.42
Post-harvest	30-60	4.0	94.0	28.8	130.8	11.0	4.6	24.5	1.40
	60-90	4.0	88.8	26.5	110.3	9.3	3.6	18.3	1.44
Average		**4.1**	**94.3**	**31.6**	**130.7**	**14.3**	**4.8**	**26.8**	**1.42**

Field 6									
Sampling period	**Depth**	**pH**	**P**	**K**	**Ca**	**Mg**	**S**	**Na**	**Bulk density**
	cm	**KCl**			**mg kg^{-1}**				**g cm^{-3}**
	0-30	4.6	63.3	30.7	190.7	33.7	12.3	18.0	1.43
Pre-planting	30-60	5.5	52.3	35.0	227.7	79.7	10.1	63.0	1.41
	60-90	5.7	10.0	36.3	450.7	406.3	9.3	211.0	1.29
Average		**5.3**	**41.9**	**34.0**	**289.7**	**173.2**	**10.6**	**97.3**	**1.38**
	0-30	5.1	56.0	44.0	198.0	38.0	22.4	65.0	1.37
Post-harvest	30-60	4.9	35.0	47.0	176.0	26.0	28.6	45.0	1.45
	60-90	4.6	41.0	37.0	162.0	25.0	17.9	37.0	1.48
Average		**4.8**	**44.0**	**42.7**	**178.7**	**29.7**	**23.0**	**49.0**	**1.43**

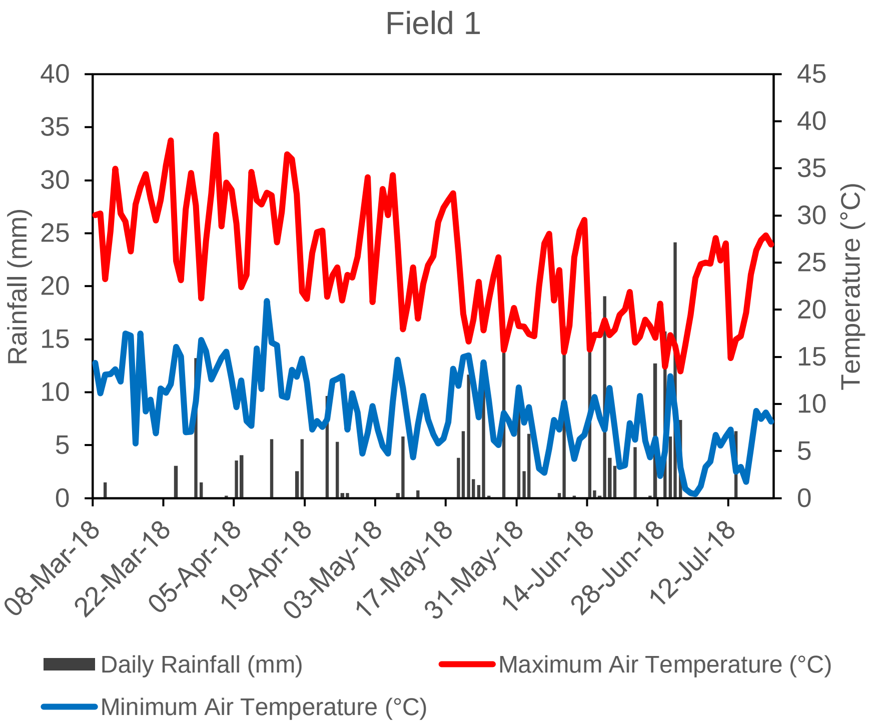
Field 7									
Sampling period	**Depth**	**pH**	**P**	**K**	**Ca**	**Mg**	**S**	**Na**	**Bulk density**
	cm	**KCl**			**mg kg^{-1}**				**g cm^{-3}**
Pre-planting	0-30	5.1	29.8	22.3	187.5	20.3	8.0	18.3	1.46
	30-60	4.6	18.0	17.8	120.0	13.0	2.8	14.3	1.49
	60-90	4.6	14.8	14.8	96.8	11.5	1.7	11.3	1.48
Average		**4.8**	**20.8**	**18.3**	**134.8**	**14.9**	**4.1**	**14.6**	**1.48**
Post-harvest	0-30	5.7	20.0	50.5	171.8	19.3	5.3	43.3	1.52
	30-60	4.9	16.0	25.0	120.8	13.5	5.0	24.3	1.50
	60-90	4.6	15.3	21.8	106.5	12.8	4.1	19.5	1.52
Average		**5.1**	**17.1**	**32.4**	**133.0**	**15.2**	**4.8**	**29.0**	**1.51**

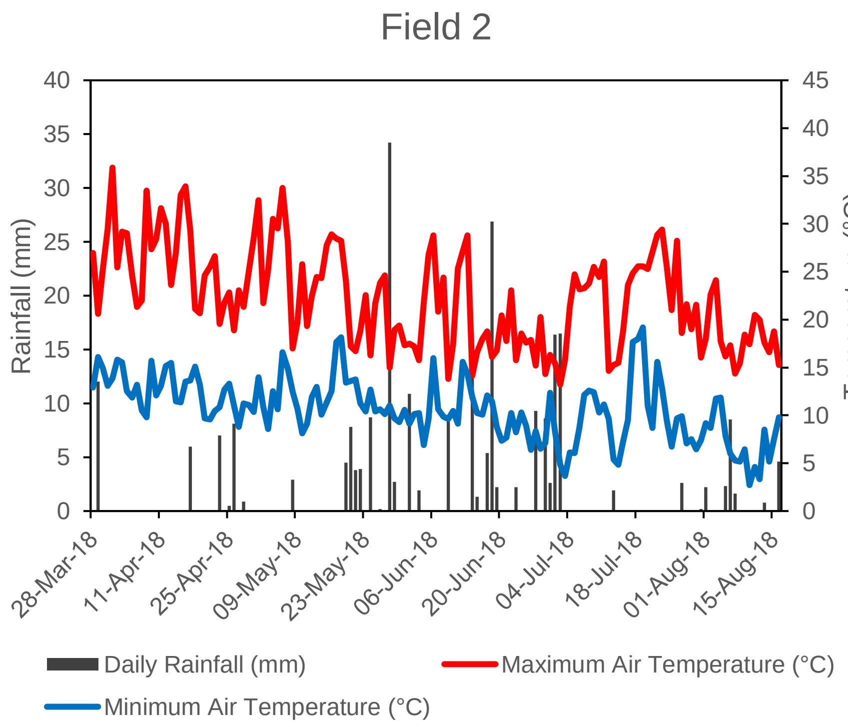
Field 8									
Sampling period	**Depth**	**pH**	**P**	**K**	**Ca**	**Mg**	**S**	**Na**	**Bulk density**
	cm	**KCl**			**mg kg^{-1}**				**g cm^{-3}**
Pre-planting	0-30	4.5	29.8	31.3	217.5	20.3	33.8	22.5	1.52
	30-60	4.4	12.5	25.5	109.0	15.0	9.6	12.8	1.53
	60-90	4.6	4.5	17.0	98.0	14.8	7.2	11.5	1.55
Average		**4.5**	**15.6**	**24.6**	**141.5**	**16.7**	**16.8**	**15.6**	**1.53**
Post-harvest	0-30	5.2	17.5	17.5	158.0	14.3	25.8	7.2	1.53
	30-60	4.8	12.3	5.8	126.3	5.3	24.5	3.9	1.51
	60-90	5.2	6.3	5.8	116.3	4.3	22.8	3.1	1.52
Average		**5.1**	**12.0**	**9.7**	**133.5**	**7.9**	**24.3**	**4.7**	**1.52**

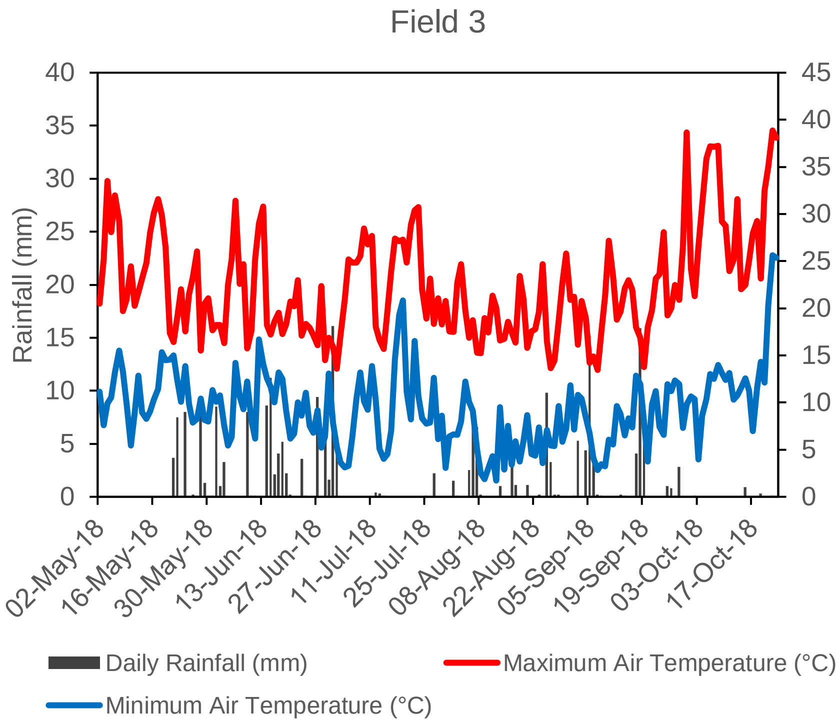
				Field 9					
Sampling period	**Depth**	**pH**	**P**	**K**	**Ca**	**Mg**	**S**	**Na**	**Bulk density**
	cm	**KCl**			**mg kg^{-1}**				**g cm^{-3}**
	0-30	4.9	18.8	12.3	198.3	36.3	17.7	36.8	1.56
Pre-planting	30-60	4.9	15.0	11.5	174.8	32.5	14.7	34.5	1.56
	60-90	4.5	13.8	11.3	112.5	21.8	11.8	29.8	1.57
Average		**4.8**	**15.8**	**11.7**	**161.8**	**30.2**	**14.7**	**33.7**	**1.57**
	0-30	5.0	13.5	10.5	150.5	22.8	7.1	23.3	1.54
Post-harvest	30-60	4.9	10.3	6.5	125.8	15.5	4.7	21.5	1.54
	60-90	4.7	11.8	6.3	101.5	10.0	5.0	20.8	1.55
Average		**4.9**	**11.8**	**7.8**	**125.9**	**16.1**	**5.6**	**21.8**	**1.54**

APPENDIX III

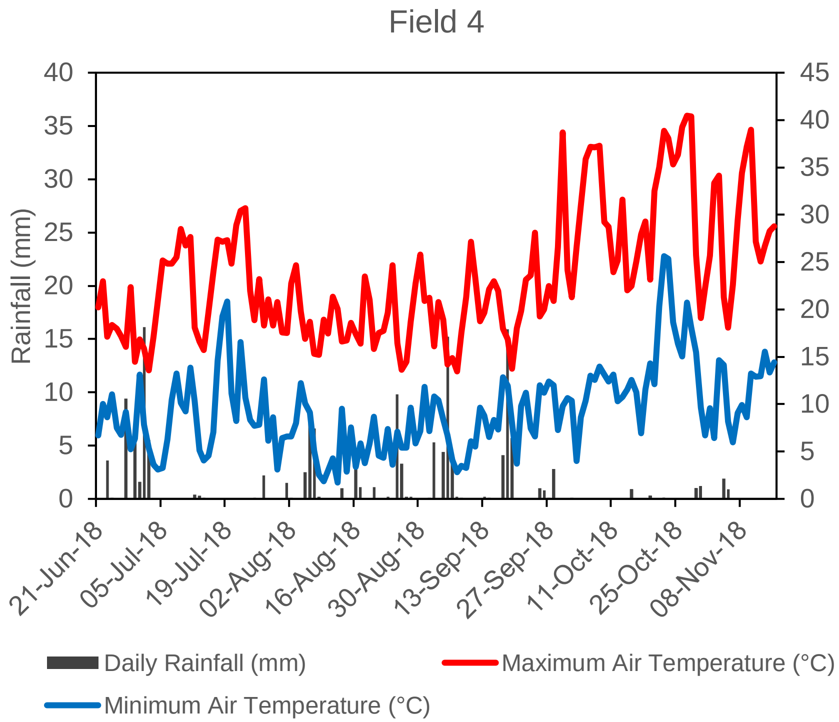
Appendix IIIa. Daily fluctuations in maximum and minimum air temperatures as well as daily rainfall occurrences for all monitored fields in the Sandveld region. Any missing data, due to delayed installation of weather stations, was corrected for with weather stations located within the vicinity of the fields.



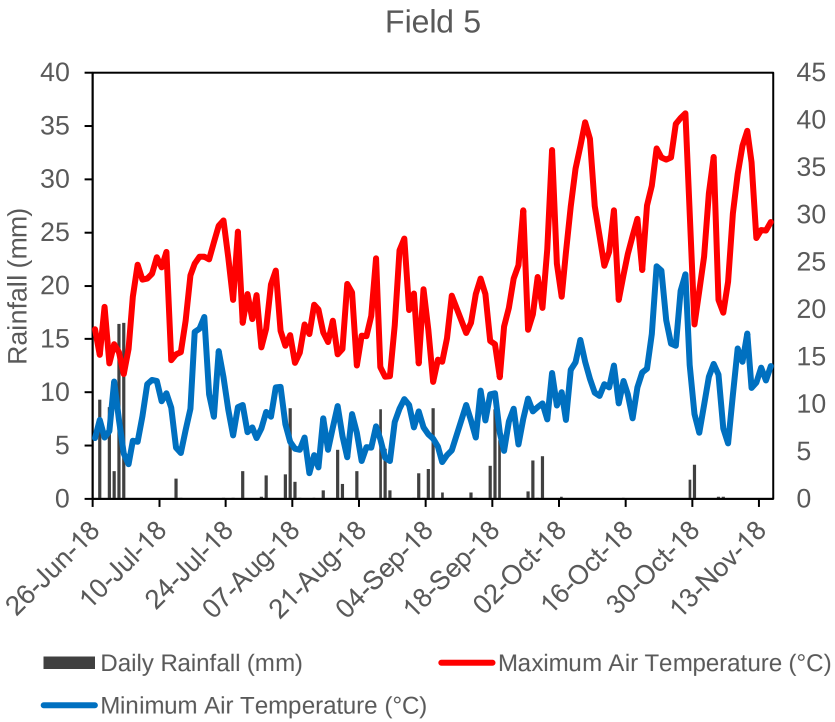




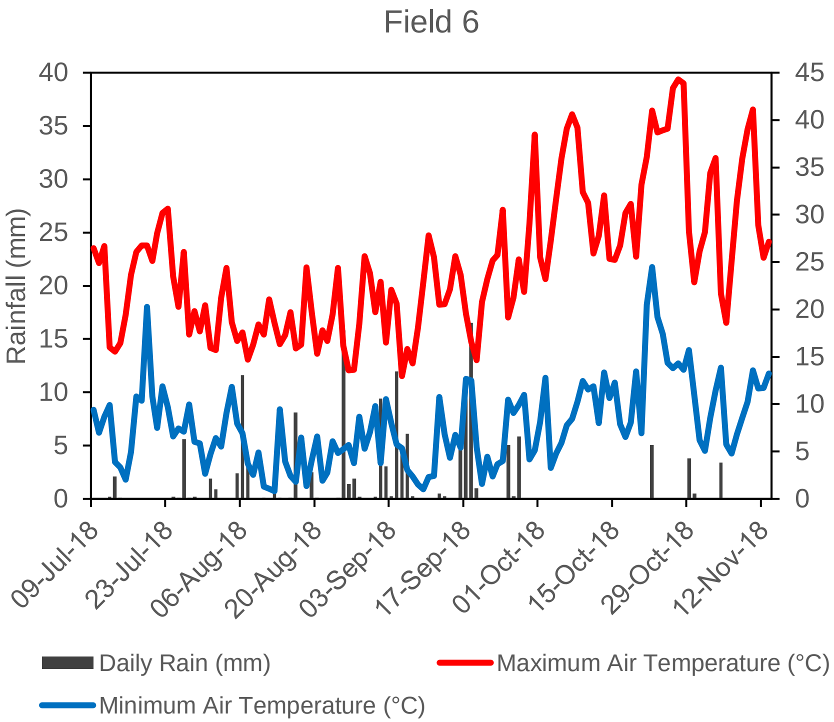
Field 3
Rainfall (mm)
Temperature (°C)
0
5
10
15
20
25
30
35
40
45
02-May-18
16-May-18
30-May-18
13-Jun-18
27-Jun-18
11-Jul-18
25-Jul-18
08-Aug-18
22-Aug-18
05-Sep-18
19-Sep-18
03-Oct-18
17-Oct-18
Daily Rainfall (mm)
Maximum Air Temperature (°C)
Minimum Air Temperature (°C)



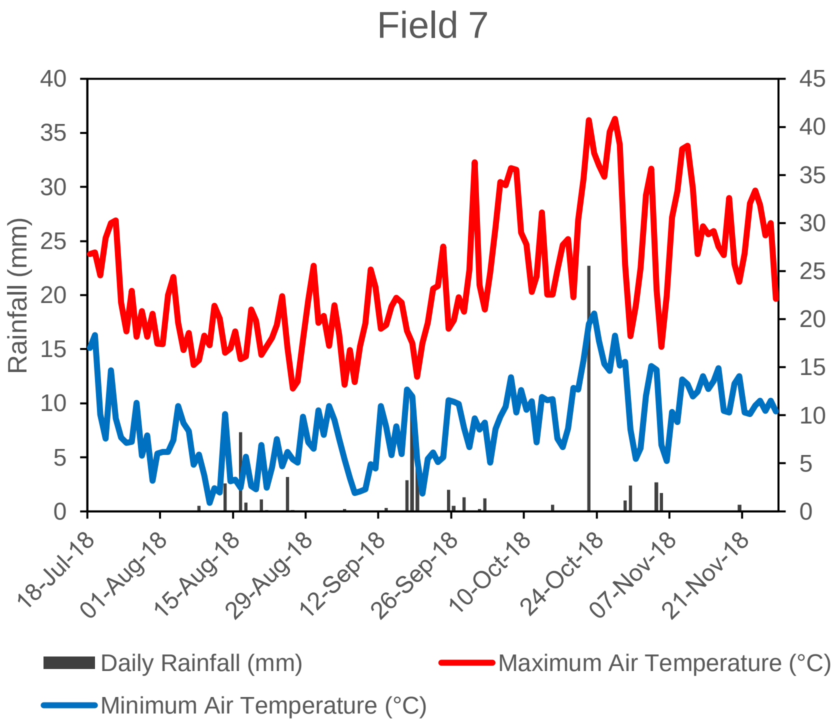
Field 4
Rainfall (mm)
Temperature (°C)
0
5
10
15
20
25
30
35
40
45
21-Jun-18
05-Jul-18
19-Jul-18
02-Aug-18
16-Aug-18
30-Aug-18
13-Sep-18
27-Sep-18
11-Oct-18
25-Oct-18
08-Nov-18
Daily Rainfall (mm)
Maximum Air Temperature (°C)
Minimum Air Temperature (°C)



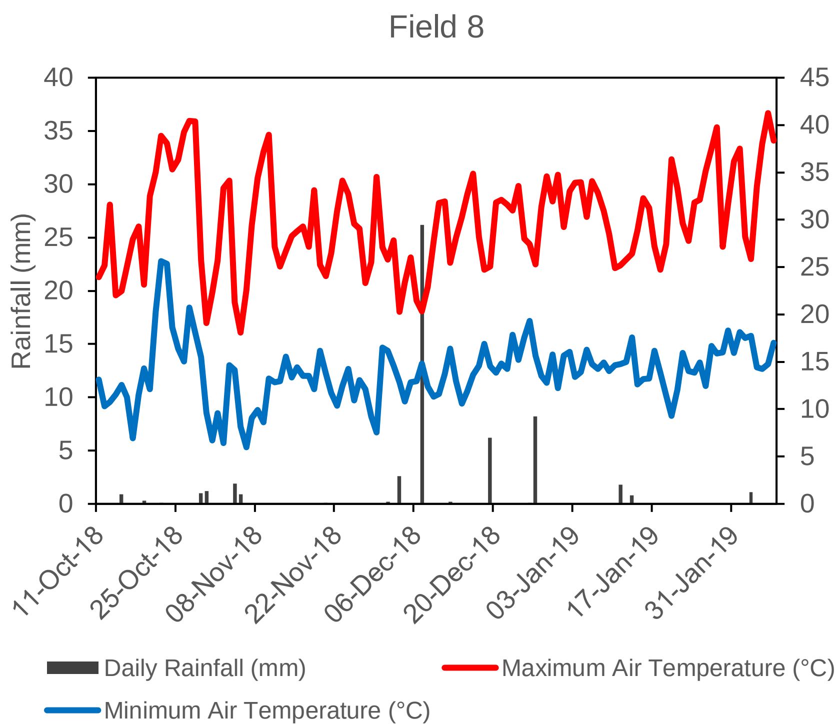
Field 5
Rainfall (mm)
Temperature (°C)
0
5
10
15
20
25
30
35
40
45
26-Jun-18
10-Jul-18
24-Jul-18
07-Aug-18
21-Aug-18
04-Sep-18
18-Sep-18
02-Oct-18
16-Oct-18
30-Oct-18
13-Nov-18
Daily Rainfall (mm)
Maximum Air Temperature (°C)
Minimum Air Temperature (°C)



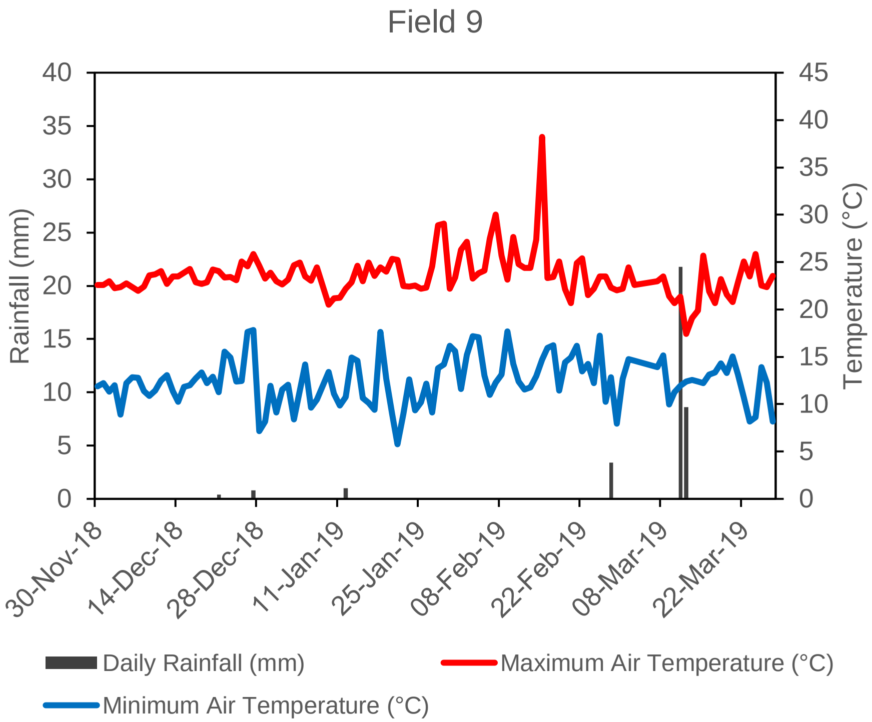
Field 6
Rainfall (mm)
Temperature (°C)
0
5
10
15
20
25
30
35
40
45
09-Jul-18
23-Jul-18
06-Aug-18
20-Aug-18
03-Sep-18
17-Sep-18
01-Oct-18
15-Oct-18
29-Oct-18
12-Nov-18
Daily Rain (mm)
Maximum Air Temperature (°C)
Minimum Air Temperature (°C)



Field 7
Rainfall (mm)
Temperature (°C)
18-Jul-18
01-Aug-18
15-Aug-18
29-Aug-18
12-Sep-18
26-Sep-18
10-Oct-18
24-Oct-18
07-Nov-18
21-Nov-18
Daily Rainfall (mm)
Maximum Air Temperature (°C)
Minimum Air Temperature (°C)



Field 8
Rainfall (mm)
Temperature (°C)
11-Oct-18
25-Oct-18
08-Nov-18
22-Nov-18
06-Dec-18
20-Dec-18
03-Jan-19
17-Jan-19
31-Jan-19
Daily Rainfall (mm)
Maximum Air Temperature (°C)
Minimum Air Temperature (°C)


Field 9
Rainfall (mm)
Temperature (°C)
0
5
10
15
20
25
30
35
40
45
30-Nov-18
14-Dec-18
28-Dec-18
11-Jan-19
25-Jan-19
08-Feb-19
22-Feb-19
08-Mar-19
22-Mar-19
Daily Rainfall (mm)
Maximum Air Temperature (°C)
Minimum Air Temperature (°C)

Appendix IIIb. Solar radiation interception as estimated using above canopy and below canopy ceptometer readings taken every second site visit (weather permitting). The percentage of intercepted solar radiation correlates to the crop canopy cover.

Field	Row Labels	Average of solar interception above canopy (μmol m^{-2} s^{-1})	Average of solar interception below canopy (μmol m^{-2} s^{-1})	Average percentage Intercepted solar radiation (μmol m^{-2} s^{-1})
Field 1	10-May-18	300	24	92
Field 2	10-May-18	1066	132	87
	11-Jul-18	509	185	64
	23-Jul-18	189	136	28
Field 3	09-Jul-18	497	102	80
	23-Jul-18	998	174	83
	21-Aug-18	808	204	74
	11-Sep-18	1491	805	46
Field 4	21-Aug-18	802	415	46
	11-Sep-18	1518	281	81
	01-Oct-18	742	122	85
	23-Oct-18	2028	1166	42
Field 5	22-Aug-18	1396	519	63
	10-Sep-18	644	34	95
	01-Oct-18	1375	85	93
	30-Oct-18	1188	464	61
Field 6	21-Aug-18	1328	840	37
	10-Sep-18	159	21	87
	01-Oct-18	722	57	92
	30-Oct-18	1790	757	57
Field 7	11-Sep-18	1524	1009	34
	01-Oct-18	560	60	89
	30-Oct-18	1264	526	57
Field 8	05-Dec-18	2038	288	86
	07-Jan-19	1888	245	87
	30-Jan-19	1032	441	57
Field 9	07-Jan-19	1007	81	92
	30-Jan-19	1507	60	96
	19-Feb-19	851	610	29